SIMULATION OF FIBER ALIGNMENT DURING THE INJECTION MOLDING PROCESS BY USING SHORT CARBON FIBER AND PDMS MIXTURE

Dong-Wook Oh* and Jun Yub Park

Department of Mechanical Engineering, Chosun University, 309 Pilmundaero, Donggu, Gwangju 61452, Korea,
*. dwoh@chosun.ac.kr

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ABSTRACT

Polymer composites are commonly used as a base structural material of many commercial products due to its light weight, cheap price, corrosion resistivity and etc. Usually, additives in forms of short or chopped fibers are frequently added to enhance the physical properties of base polymers. The material of additives varies from glass, carbon and so on, depending on the required physical property of the composites. It is important to understand the rheology of the additives during the fabrication process, such as fiber alignment inside the flow channels of the injection mold. Because the physical properties of the composites greatly rely on the additive distribution and orientation inside the matrix. However, characterization techniques of the alignment and distribution of additives are limited since it is a complicated resultant of fiber and polymer rheology, mold configuration, manufacturing method, and so on. In this paper, in order to understand the additive alignment and orientation, we perform an experiment on flow visualization of a PDMS (Polydimethylsiloxane) and carbon fiber mixture inside a transparent mold with acrylic windows. PDMS and carbon fiber imitate a molten polymer composite flow inside a mold during the polymer process such as an injection molding. The images of the fiber alignment and orientation are recorded and analyzed depending on the channel hydraulic diameter and channel configuration.

1 INTRODUCTION

Use of functional plastic is expanding rapidly due to many advantages of polymers compared to metallic materials. Productivity, low manufacturing cost, lightweight, capability of fabricating complex shaped products and chemical inertness are some of the major advantages. However, compared to metallic materials, limited use of plastics can be found in fields that need structural robustness, durability and ability to conduct electricity and/or heat. For example, a typical plastic has more than an order of magnitude smaller ultimate tensile strength and over 3 orders of magnitude smaller thermal conductivity compared to aluminum. Due to these shortcomings, plastics are known to be unsuitable for structural materials of a thermal system such as a heat exchanger. In effort to improve aforementioned disadvantages of the plastics, mixing and blending of polymers with additives that have superior physical properties such as glass, carbon, metal, ceramic and so on has been studied for recent several decades. [1-4]

Thermophysical properties of polymer composites are also becoming an important issue due to the wide spread of handheld smart devices such as smartphones and tablet PCs. While the power consumption per unit volume of such electronic devices are increasing, lighter and thermally conductive material is required due to increase the portability of the devices. For this reason, many developments has been conducted on increasing thermal conductivity of polymer composites. [4-6]

Polymer composites with carbon nanomaterials such as carbon nanotube or graphene are known to have 100 times higher thermal conductivity compared to the base polymers. In these composites, usually 1-D or 2-D structured additives in forms of fiber or flake is mixed with the base polymer. The alignment and orientation of such additives play a great role in the physical properties of the composite. This is because the physical properties such as tensile strength and thermal conductivity increases in the direction of alignment of the additives, but the improvements are known to be negligible in the vertical direction of the additive alignment.[8] Thus the additive alignment and orientation during the molding process is a critical design parameter. However, alignment of additive inside a polymer matrix depends on a very complicated rheology of the additives and molten polymeric flow during the molding process. An example of additive alignment inside a molding process is shown in Fig 1.

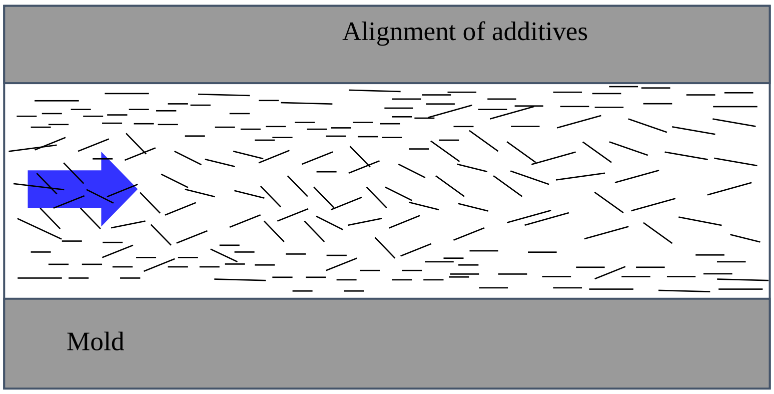

Figure 1 Additive alignment in the molten polymer composite flow inside an injection mold

Although the additive orientation plays a great role in the composite property, technique that enables quantitative analysis of the additive alignment is very limited. This is because the typical polymer composites are opaque and flow inside the mold is difficult to visualize. In this study, in order to analyze the additive alignment and orientation during an injection molding process, flow visualization of Polydimethylsiloxane (PDMS) and chopped carbon fiber mixture is performed. The flow channels are fabricated by a 3D printed plastic block with an acrylic transparent widow. Captured images depending on various mold configurations are analyzed to understand the behavior of fiber movement during the injection molding process of polymer composites.

2 EXPERIMENTAL METHOD

An experimental setup as shown in Fig. 2 is prepared to analyze the carbon fiber alignment and orientation during an injection molding process. The molten polymer flow inside a mold is simulated by a liquid PDMS and carbon fiber mixture flow inside a flow channel. The liquid state PDMS is prepared by mixing 10:1 ratio of base and curing agents of Sylgard 184 (Dow Corning Co.). Milled carbon fiber (MFC, DowAksa Co.) powder is then added to the PDMS. The weight concentration of the carbon fiber is fixed at 0.05%. Average diameter and length of a carbon fiber is known to be 7 μm and 0.1 mm, respectively. PDMS and carbon fiber mixture is put in a vacuum chamber for degassing.

The vacuum chamber is maintained at 0.1 Torr and degassing is performed for 20 minutes. Additional care is put on the PDMS and carbon fiber mixture so that air bubble does not get trapped during the preparation process.

The flow visualization experimental setup can be classified into the mold, pumping unit and imaging parts. The flow channel that simulates the mold is fabricated by a 3D printer (Objet Eden 260VS, Stratasys Ltd.) The flow channels are consist of a "n" shaped channel with 4, 90° elbows and a 20 mm straight section as shown in Fig. 3. 3 types of flow channels with 0.4, 0.8 and 1.8 mm channel thickness are fabricated. The channel width is fixed to 20 mm. 2 transparent acrylic plates are fasten to the flow channel on the front and back sides for channel sealing. 5 bolts with washers and nuts are used to hold the acrylic plates at 5 holes to the 3D printed channel block. Flow visualization is performed at the red circle areas shown in Fig. 3. Flow visualization images at the second 90° turning elbow and straight channel region are recorded and the fiber alignments are analyzed.

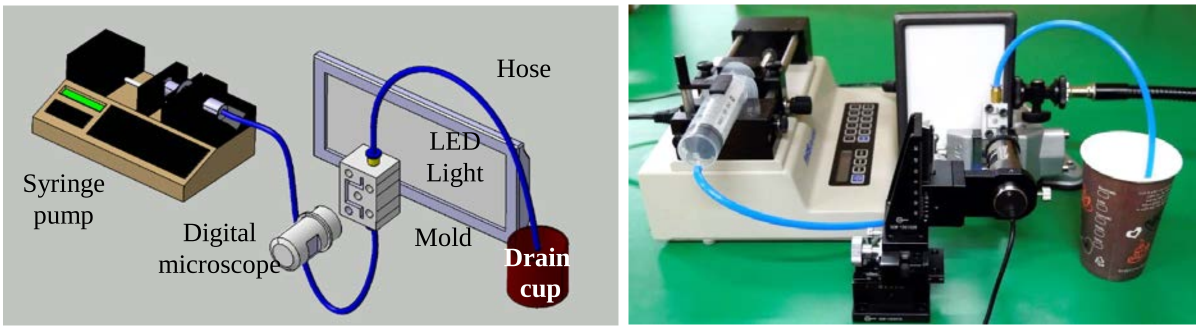

Figure 2 Schematic and pictures of the experimental setup for flow visualization.

Mixture of PDMS and carbon fibers are loaded on a high pressure syringe pump (KDS410, KD Scientific Inc.) inside a 50 mL syringe. The pumping speed of the syringe pump is controlled to achieve a creeping flow of Re=1.2×10^{-4} at the visualization locations. The flow channel blocks are connected from the syringe with a polypropylene tube of 6mm inner diameter. A paper cup is used as a drain cup to hold the flowing PDMS and carbon fiber mixtures as shown in Fig. 2.

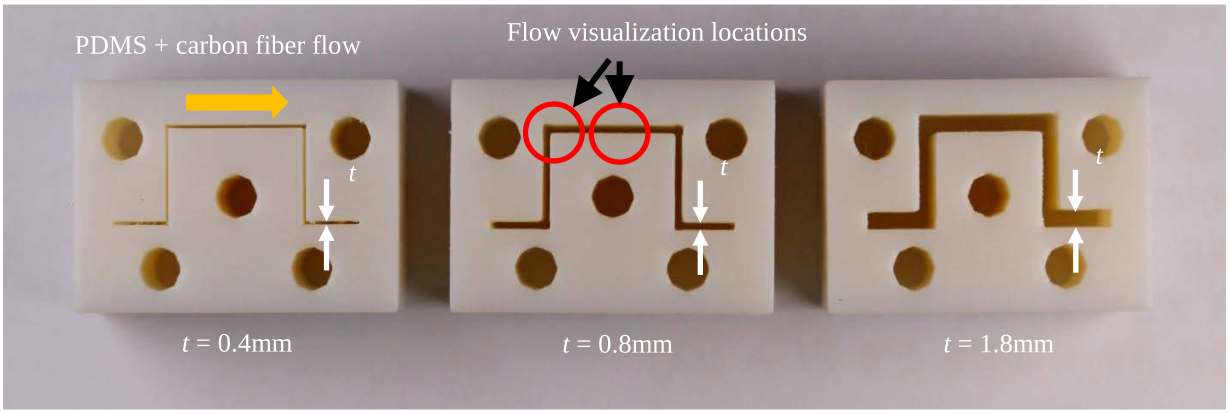

Figure 3 3 types of flow channel blocks fabricated by a 3D printer.

Flow visualization images are recorded through a digital microscope (AM7515, AnMo Electronics Co.) A 11W LED light positioned at the back of the channel block as shown in Fig. 2 provided a sufficient lighting for the flow visualization. The images are recorded in 10 frames per second and with 100 time magnification. The microscope and the channel block is positioned by a 3 axis stages and focal plane in the flow channel is set to be 2 mm inside the inner surface of the acrylic plate.

3 RESULTS

The flow visualization images of PDMS and carbon fiber mixture are shown in Fig 4 and 5. The flow visualization results of a straight and 90^o elbow channels with thicknesses varying by 0.4, 0.8 and 1.8 mm are depicted in Fig. 4 and 5, respectively. The Re number is fixed at 1.2×10^{-4} for all experimental results. The actual length of the carbon fibers are found to distribute between 0.1 to 2 mm from the observation of flow visualization images. As shown in the pictures most of the fibers inside the flow is considered to be aligned to the direction of the flow regardless of the channel thickness.

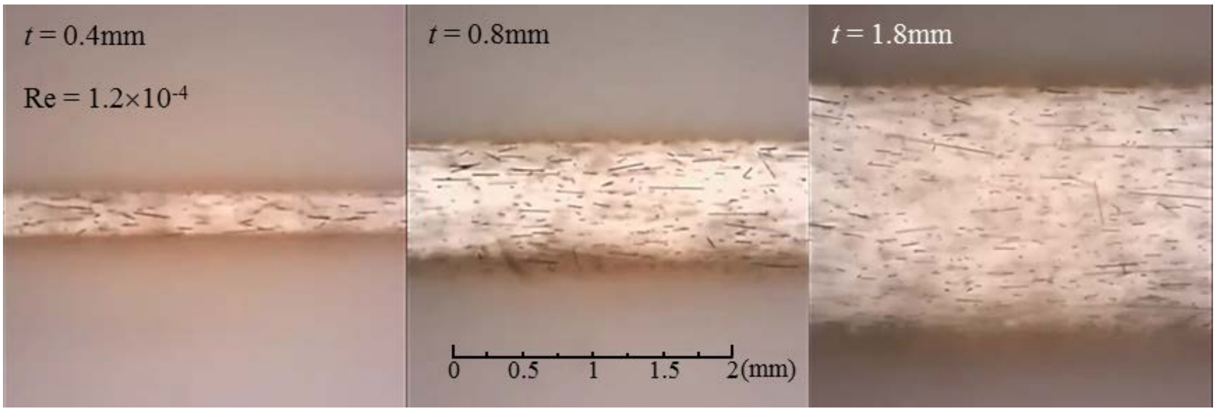

Figure 4 Additive alignment in a straight channel flow of channel thickness *t*=0.4 mm, 0.8 mm and 1.8 mm.

In Fig. 4, flow visualization images of PDMS and carbon fiber mixture in straight channel flow are presented according to the channel thickness variation of 0.4, 0.8 and 1.8 mm. The fiber alignment along the channel is very similar regardless of the channel thickness variation. The fibers flowing close to the wall region is considered to be exposed to maximum shear stress inside the channel. The shear stress exerted on the fiber acts as a driving force of rotation and alignment in the flow. Theoretically, fibers located on the wall side where the shear stress is maximum, tends to be aligned to the flow. However, in the center region where velocity gradient along the channel thickness direction is minimum, force exerted on the fiber by the shear stress is smaller compared to the wall region. Resulting fiber orientation at the channel center should become more randomly distributed. The experimental results of thinner channels (0.4 mm and 0.8 mm cases) does not show the aforementioned trend. However, flow visualization image of 1.8 mm channel thickness case clearly shows randomly oriented fibers in the middle and mostly aligned fibers on the wall region. Some minor miss-aligned fibers are thought to be affected by fiber-fiber and/or fiber/wall interactions such as collision between fibers and fiber and the wall.

90^o elbow channel flow of PDMS and carbon fiber mixtures are shown in Fig 5. Compared to the straight channel flow, fiber alignment and orientation shows a very different trend. The flow in the elbow channel is no longer symmetric to the channel center line. The fiber orientation is observed to depend on the radius of curvature of the fiber flow path. Those fibers flow in the convex corner undergo a quick and accelerated turn compared to the fibers flowing near to the concave corners. Furthermore, dead space where velocity becomes close to ‘0’ can be noticed at the concave corner and velocity of fibers pathing such region is deaccelerated and undergo a slow turn.

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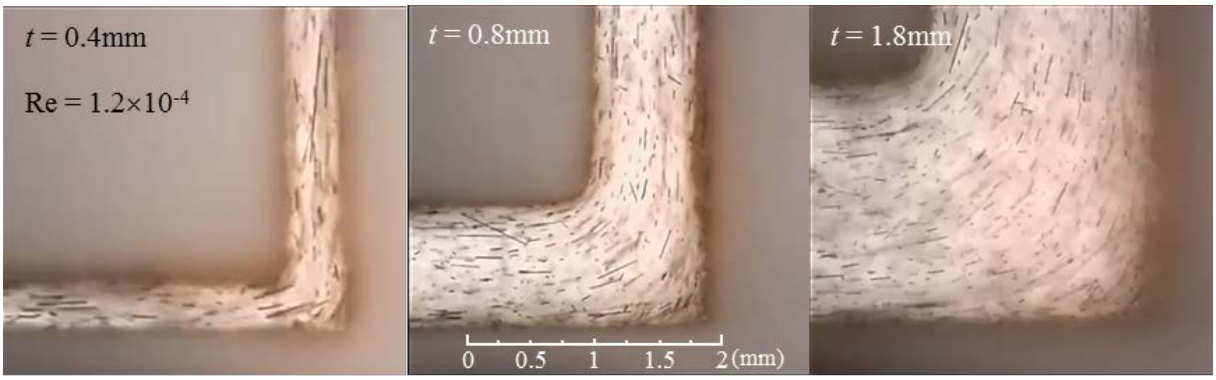

Figure 5 Additive alignment in a 90° elbow channel flow of channel thickness *t*=0.4 mm, 0.8 mm and 1.8 mm.

4 CONCLUSION

In this paper, a mixture of PDMS and milled carbon fiber are used to simulate a molten polymer composite flow during an injection molding process. Flow visualization is enabled by utilizing a 3D printed mold block and transparent acrylic plate windows as the observation mold. Flow of a transparent PDMS with milled carbon fiber mixture inside the channel is recorded with a digital microscope. From the obtained images, fiber alignment and orientation inside the mold channel are analyzed. Flow visualization experiments are performed for a straight and 90° elbow channels with channel thickness ranging from 0.4 to 1.8 mm.

Most of the fibers in the flow are observed to be aligned to the direction of the flow. Few fibers in the center of the channel is thought to be randomly oriented compared to the fibers traveling close to the wall region for the straight channel flow case. In the 90° elbow channels, fiber movements at the convex and concave corner show significantly different trend. The proposed flow visualization technique can be applied to obtain further understanding of anisotropic physical property of polymer composite with fiber type additives.

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