FIBER ORIENTATION AT THE MID-PLANE IN INJECTION MOLDING OF REINFORCED THERMOPLASTICS

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ABSTRACT

Injection molding of fiber-reinforced thermoplastics is able to open a new dimension in the area of mass production of complicated net-shaped parts with accurate dimensions while the new target could be the production of parts with tailored properties. This experimental study reveals the complex flow behavior in the filling and packing phases of injection molding process and shows its effect on fiber orientation at the mid-plane of the final product. The effects of melt and mold temperature are also studied and correlated to the observed fiber patterns.

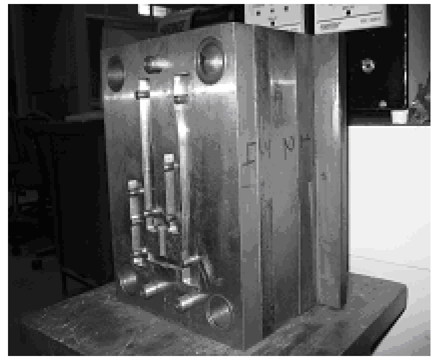
1. INTRODUCTION

Thermoplastics coupled with fibers, as reinforcement, offer a number of advantages in terms of end-use performance of the products in the process of injection molding. However, the properties of the final products are strongly affected by the fiber orientation field set up during processing. Depending on the selected process conditions, the orientation of fibers varies significantly at the mid-plane and across the thickness of injection-molded part and becomes a key feature of the finished product. There are lots of confusions in the conclusion of many studies in explaining the effect of packing pressure [1, 2, 3, 4, 5], melt [1, 6, 7, 8, 9] and mold [1, 4, 10] temperature on the state of fiber orientation. Since packing pressure has a significant effect on compensating in-mold shrinkage and mold temperature provides a wide range of possible process conditions, the present work is concentrated on analyzing the state of fiber orientation at the mid-plane during filling and packing phases of injection molding process by considering the effects of melt and mold temperature.

2. MATERIALS AND METHODS

RGF33 NATURAL (TUFNYL, SRF Made), a 33% by weight short glass fiber reinforced in PA66, was used in the experiments of this study. For analyzing the orientation of fibers in injection molding process, two molds namely Spiral Mold and Test Samples Mold were used. The cavities of the molds are shown in Fig. 1.

a. Spiral Mold



b. Test Sample Mold

Figure 1: Cavities of Spiral Mold and Test Sample Mold

To avoid any change in the state of fiber orientation due to sudden increase of pressure after complete filling of the cavities, short shot products of each mold are used for studying the state of fiber orientation during the filling phase of injection molding process.

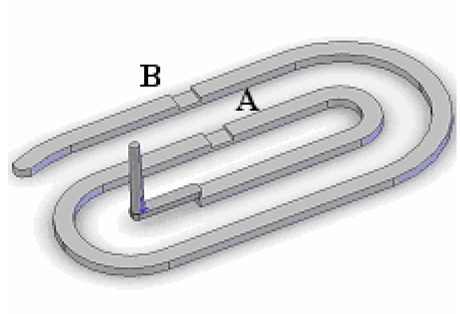
For analyzing the state of fiber orientation during flow and packing phases nine cases with various process conditions, as shown in Table 1, were studied. In this nomenclature "I" refers to the products of spiral mold and "J" refers to the products of Test Samples mold while "DF" is the abbreviation of "During Flow", "JF" refers to "Just Filled" products and "P" represents "Packed" samples. "II" is used for the products of the mold with higher melt temperature and "III" is used for the products of higher mold temperature.

Table 1: Process conditions

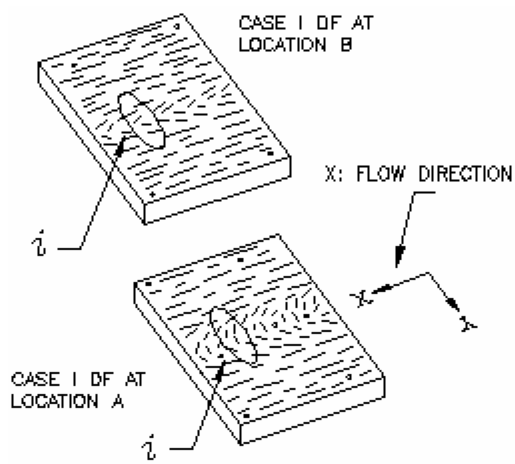
Case	Melt Temperature (ºC)	Mold Temperature (ºC)	Pressure (%Max Hydraulic Pressure)
I DF	290	35	0
II DF	305	35	0
III DF	290	79	0
I JF	290	35	0
I P	290	35	40
J DF	290	35	0
J JF	290	35	0
J CF	35	290	0
J P	35	290	20

3. RESULTS AND DISCUSSION

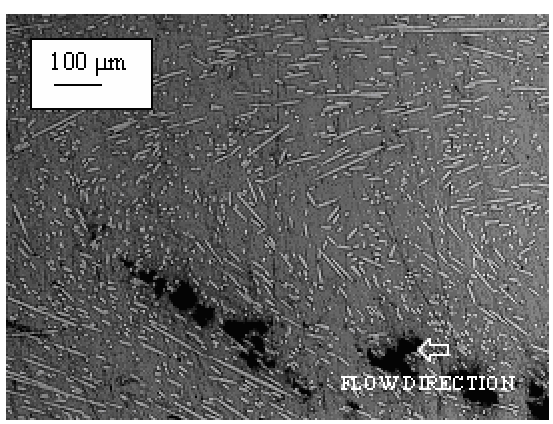
For studying the state of fiber orientation along the flow length and during the filling phase, patterns of fiber orientation at the mid-plane of locations A & B in Case I DF are shown in Fig. 2. The observed patterns of fiber reveals the state of velocity profile along the flow direction and shows the importance of heat conduction in the y-direction which is perpendicular to the flow direction as shown in Fig. 2b. This important parameter is neglected by Kennedy [11], Lee et al. [3], and Bay & Tucker [2] during simplification of the energy equation for the filling phase.



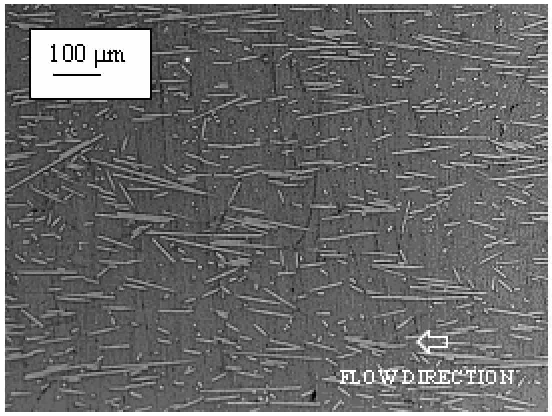
a. Cut-sections at the mid-plane parallel to the plane of flow at locations A & B



b. Schematic patterns of fiber orientation at locations A & B



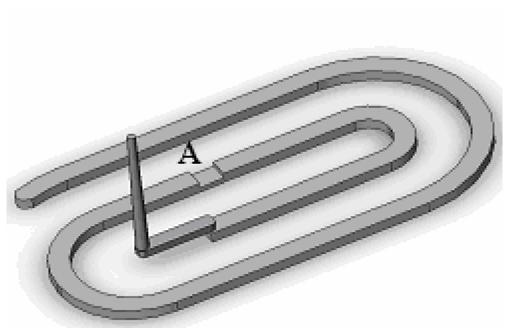
c. Transverse orientation of fibers at the centerline of mid-plane at location A



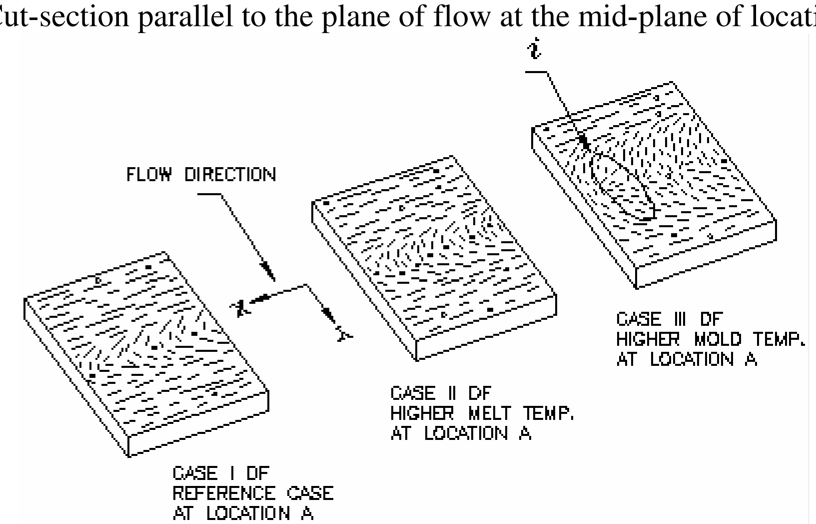
d. Alignment of fibers with the flow direction at the centerline of the mid-plane at location B

Figure 2: State of fiber orientation at locations A & B (Case I DF)

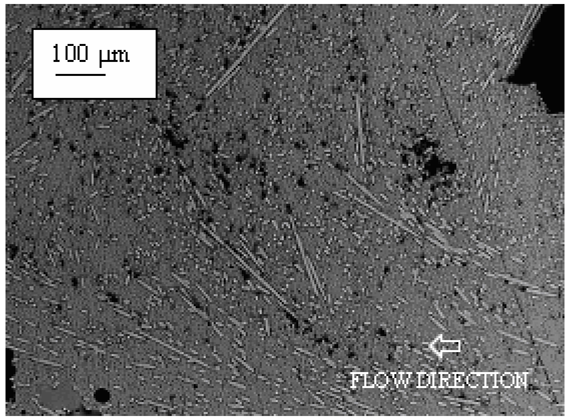
Increasing melt and mold temperature affects the state of fiber orientation at the mid-plane of location A significantly, as shown in Fig. 3.



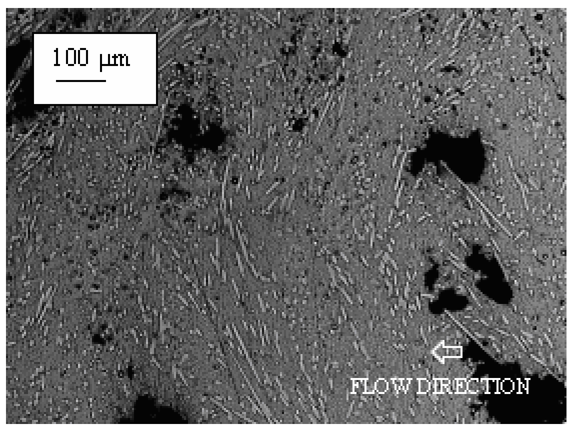
a. Cut-section parallel to the plane of flow at the mid-plane of location A



b. Patterns of fiber orientation at location A (Cases I DF, II DF and III DF)



c. Wider band of transverse orientation of fibers at the centerline of location A (Case II DF)



d. Highest degree of transverse orientation of fibers at the centerline of location A (Case III DF)

Figure 3: State of fiber orientation at the higher melt and mold temperature (Case II DF & III DF) and its comparison with Case I DF- Spiral Mold

These peculiar patterns of fiber, which show a combination of shearing flow and diverging flow (stretching flow) at the mid-plane, are not in agreement with the idea of Fischer [12] who believes that at the core layer of the part, the melt being pushed forward develops a flattened profile and fibers within this region do not orient without a well-developed shear flow. These results are also in contrast to the idea of Bay & Tucker [2] who believe that the strip geometry has no in-plane deformation, and therefore the gap-wise shearing flow would be the dominating factor in orienting the fibers.

Comparing the fiber patterns in short shot products with completely filled and packed ones is the basic procedure at the next step. Patterns of fiber orientation at the mid-plane of location A for Case I in its three different conditions (I DF, I JF and I P) are shown in Fig. 4. The results of this study reveal the important effect of packing pressure on the final state of fiber orientation.

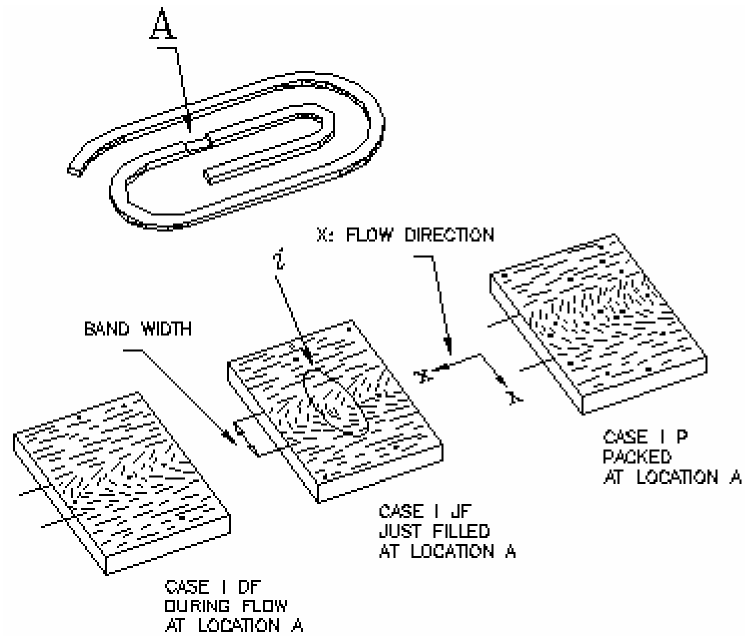
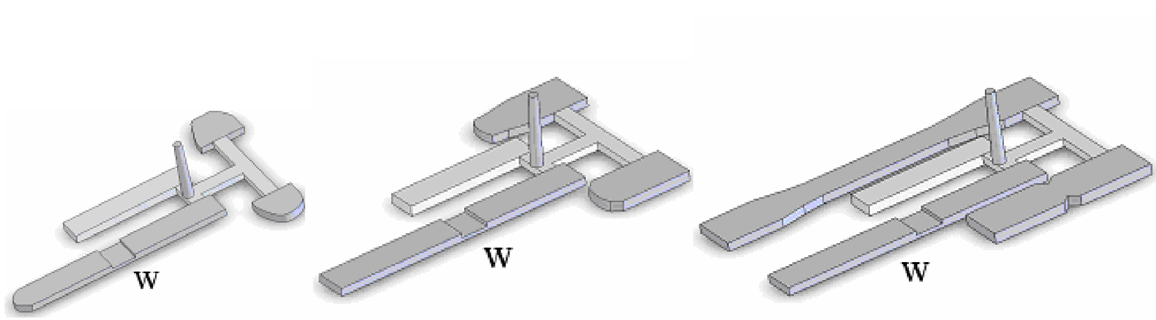
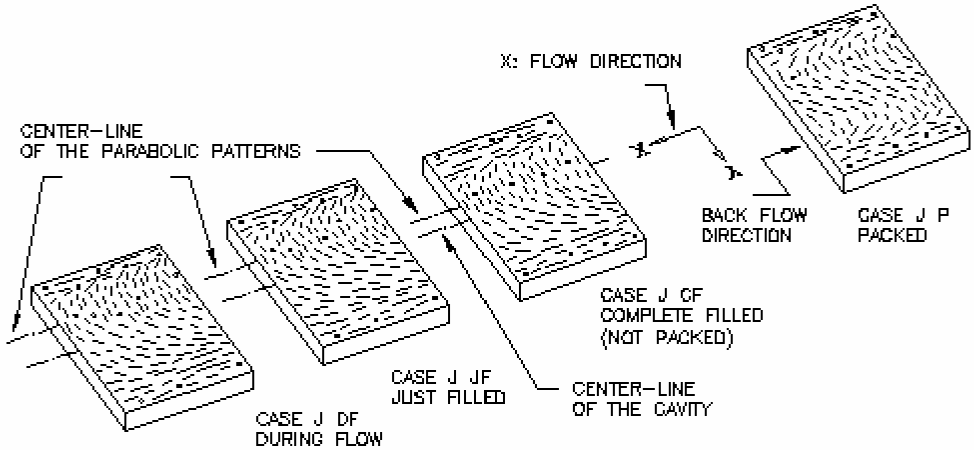


Figure 4: Patterns of fiber orientation at location A (Cases I DF, I JF, and I P)

Comparing the bandwidth of parabolic patterns of fiber shows a higher degree in transverse orientation of fibers with respect to the flow direction at the mid-plane of Case I P.
This result was achieved easily just because of the type of selected cut-section. In the packing phase, in contrast to the filling phase, thickness-wise (gap-wise) cut-sections cannot always provide proper information about the state of fiber orientation and this will be explained more in analyzing the next experiment.
For finding a better observation of flow behavior during the packing phase, cut-sections at location W in different cases of Test Samples Mold were studied and the state of fiber orientation at the mid-plane of this location in Cases J DF, J JF, J CF and J P are presented schematically in Fig 5. Arrangement of fibers in Case J P represents a kind of backward flow of melt during the packing phase. Presence of backward flow is the most important effect of packing pressure. Having flow streams in opposite directions verifies that packing pressure does not pressurize melt hydrostatically and in contrast to the idea of Kennedy [11], the cavity is not being filled volumetrically.



a. Cut section W at the same location of various products - Test Sample Mold



b. Patterns of fiber orientation at the mid-plane of location W

Figure 5: Part condition, location of cut-section, and patterns of fiber orientation at the mid-plane of location W - Test Samples Mold (Cases J DF, J JF, J CF, and J P)

The unsymmetrical gate location causes an asymmetric state of viscosity in the y-direction with respect to the center-line of the cavity and results into the presence of asymmetric patterns of fiber in the plane of flow. This observation emphasizes further the importance of heat conduction in the y-direction which is an ignoring parameter in modeling the flow behavior in the packing phase by Kennedy [11].

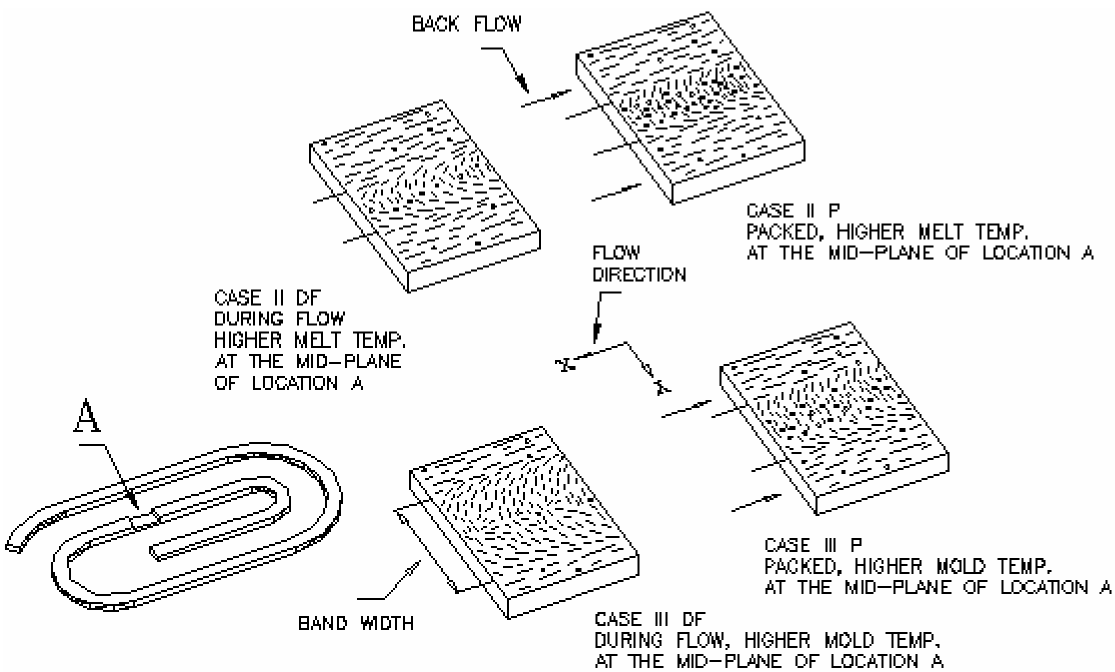


Figure 6: Effect of back flow at the mid-plane of location A (Cases II DF, II P, III DF, and III P)

Surprisingly for a higher melt and mold temperature (Cases II and III), the bandwidth of parabolic arrangement of fibers in the "Packed" products of Spiral Mold decreases compared to the "During Flow" samples and this result is in contrast to the earlier achieved results for Case I. The state of fiber orientation at the mid-plane of location A in Spiral Mold for Cases II DF, II P, III DF, and III P is shown in Fig. 6. By accepting the presence of back flow in the packing phase of injection molding process, this strange result, the decrease in the bandwidth of parabolic arrangement of fibers in Cases II P and III P, can be attributed to the presence of a kind of backward flow along the lateral sides of the cavity. Since the width of the cavity in Spiral Mold is less than the width of the cavity in Test Samples Mold, there is not sufficient space for re-arrangement of the fibers in the form of reverse parabolic patterns at the mid-plane. In this case, the backward flow in the packing phase, by aligning the previously in-plane tilted fibers during the filling phase along its own direction, causes even further alignment of fibers parallel to the flow direction along the lateral sides of the mid-plane. The direction of this assumed back flow, whose presence does not have clear evidence, is shown in Figs. 6 and 7.

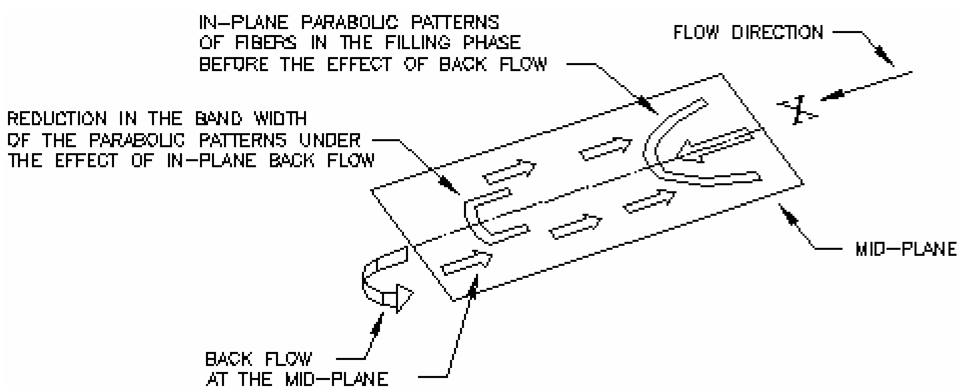


Figure 7: Backward flow at the mid-plane and its effect on increasing the alignment of fibers along the lateral sides of the cavity

In Case III P, presence of very clear backward flow was observed in layers above and below the mid-plane at the other locations. Presenting these results was ignored since they are not in the scoop of this work.

4. CONCLUSIONS

Fibers follow specific patterns according to the velocity field at the mid-plane of a cavity which show a combination of shearing flow and diverging flow (stretching flow) at the mid-plane, therefore the state of fiber orientation cannot be considered generally random.

Increasing melt & mold temperature increases the degree of transverse alignment of fibers at the mid-plane during the filling stage in injection molding process.

The results of this study emphasize the importance heat conduction in the y-direction (width of the cavity) during the filling and packing phases.

Fibers tend to get more transverse orientation along the centerline of the stretching flow (extensional flow) at the mid-plane during the packing phase of injection molding process.

Flow streams in the opposite directions co-exist in the packing phase and the presence of backward flow shows clearly that packing pressure do not pressurize the melt hydrostatically and the cavity is not being filled volumetrically during the packing phase.
Due to the presence of backward flow of melt and its interface with the forward flow during the packing phase, analyzing the state of fiber orientation just by observing the gap-wise cut-sections may lead to a set of confusing results. For having a correct conclusion in studying the state of fiber orientation during the packing phase, analyzing the cut-sections in at least two perpendicular planes is necessary.

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