INFLUENCE OF INJECTION MOLDING PROCESS PARAMETERS ON FATIGUE PERFORMANCE OF SHORT GLASS FIBER REINFORCED POLYAMIDE-6,6

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Abstract

This paper presents the results of an experimental study exploring the effects of five key injection molding parameters on the fatigue performance of 33-wt.% short E-glass fiber reinforced polyamide-6,6. The injection molding parameters selected in this study were melt temperature, mold temperature, injection pressure, injection speed and hold pressure. Each parameter was varied at two levels. The fracture surfaces were examined under scanning electron microscope to ascertain the dependence of failure process on injection molding parameters. The flow orientation of fibers due to varying injection molding parameters was determined using Moldflow software.

1 Introduction

Injection molding is the most common manufacturing process for polymer products in automotive, industrial and consumer industries. Since many of these polymer products may be subjected to fatigue cycling, it is of interest to learn the effects of injection molding parameters on the fatigue properties of polymers. Currently there are a limited number of publications on this topic [1-4]. This study was undertaken to experimentally determine the effects of key injection molding parameters on the fatigue properties of a short E-glass fiber reinforced polyamide-6,6.

2 Experimental

2.1 Material and Injection Molding Conditions

The material investigated in the study was a short E-glass fiber reinforced polyamide-6,6, which is available from DuPont, under the trade name Zytel 70G33HS1L. The reported fiber content in Zytel 70G33HS1L is 33% by weight, which is equivalent to 18% by volume. The test specimens were injection molded in a 3-cavity mold (Figure 1) and polymer melt flow took place through a single gate at the end of each cavity. Only the dog-boned shaped tensile specimens were used for tensile and fatigue experiments in this study. The specimen thickness was 3.2 mm.

The process parameters varied in the injection molding process were melt temperature, mold temperature, injection pressure, injection speed and hold pressure. Each parameter was varied at two levels (Table 1). A full factorial design of experiments was used in this study. Since there were five independent parameters, the total number of injection molding trials was 2^5 or 32. The injection molding parameters that were maintained constant were back pressure, suck back, holding speed, holding time, screw RPM and changeover.

A set of ten specimens were molded for each injection molding trial. The pellets were dried at 80°C for two hours before starting the injection molding trial. In all injection molding trials, the screw RPM was maintained at the same value and the barrel temperature was adjusted to change the melt temperature.

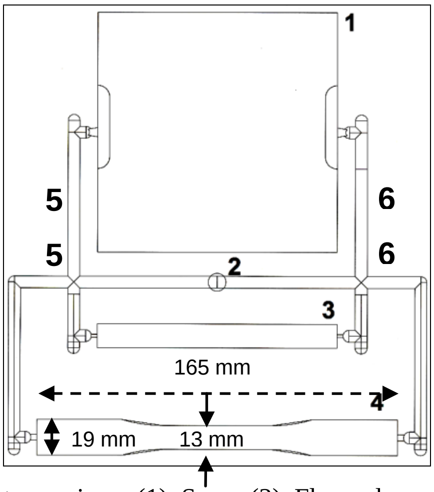

Figure 1. Mold Design – Plate specimen (1), Sprue (2), Flexural specimen (3), Tensile and fatigue specimen (4), Flow routing valves (5 and 6)

Parameter	Levels	
	Level 1	Level 2
Melt Temperature (°C)	260	288
Mold Temperature (°C)	49	99
Injection Pressure (MPa)	82.7	103.4
Hold Pressure (MPa)	20.7	41.3
Injection Speed (%)	36	50

Table 1: Injection Molding Parameters

2.2 Tension and Fatigue Tests

Both tensile and fatigue tests were conducted at room temperature (≈23 °C) on an MTS 810 servo-hydraulic testing machine. A strain rate of 5 min^{-1} was applied on the specimen during the tension tests. Of the ten specimens available for each injection molding trial, three were randomly selected for tension tests and the remaining seven specimens were also randomly selected tested for fatigue tests. Stress-controlled cyclic fatigue tests were performed in tension–tension mode at a cyclic frequency of 2 Hz. The ratio of the minimum cyclic stress and the maximum cyclic stress, the R-ratio, was 0.1. The maximum cyclic stress was varied at four levels, namely 80, 70, 60 and 50% of the tensile strength of the material.

All of the specimens tested at 60, 70 and 80% stress levels failed at less than 100,000 cycles; however, most of specimens tested at 50% stress level survived 500,000 cycles and did not fail. The surviving specimens were fatigue tested at 60% stress level until failure occurred. Using the number of cycles to failure at 60% stress level in the two-level fatigue tests, the fatigue life at 50% stress level was estimated using the Miner's linear damage rule, which for two stress level cyclic tests is given by the following equation.

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} = 1 \tag{1}$$

In Equation (1), n_1 and n_2 are the number of cycles at stress levels 1 and 2, respectively, and, N_1 and N_2 are the fatigue lives at the same two stress levels. In this study, for the specimens that did not fail till 500,000 cycles at 50% stress level, n_1 = 500,000. N_1, the fatigue life at 50% stress level, is the estimated fatigue life at 50% stress ratio, which is calculated from Eq. (1).

3 Results

3.1 Tensile Strength

For all the injection molding conditions considered in this study, the average tensile strength of the material ranged from 122 to 135 MPa. Melt temperature and mold temperature had the greatest effect on the tensile strength, with higher melt temperature and higher mold temperature resulting in lower tensile strength. Injection pressure and hold pressure had much smaller effects and injection speed had the least effect on the tensile strength.

3.2 Fatigue S-N Diagrams

The stress-life (S-N) diagrams were plotted on semi-log axes using stress ratio, i.e., the ratio of the maximum cyclic stress and the average tensile strength of the material at the processing condition considered, as the vertical axis or S-axis. The S-N diagrams were divided into two regions showing the experimental data and estimated data. Experimental data is the region from 0 through 500,000 cycles. Estimated data is the region beyond 500,000 cycles, consisting of data obtained by using Equation (1). The S-N curves were drawn through the average cyclic life values at each stress level.

Figure 2 shows four S-N curves at two different injection pressures, 82.7 MPa and 103.4 MPa and two different injection speeds, 36% and 50%. The melt temperature, mold temperature and hold pressure were 260^{o}C, 49^{o}C and 41.3 MPa, respectively. It can be observed in Figure 2 that higher injection pressure resulted in increased fatigue life of the material. Similarly, fatigue life increased when the injection speed was increased from 36% to 50% at both injection pressures.

In Figure 3, the influences of melt temperature and hold pressure are shown at the mold temperature of 49^{o}C, injection speed of 50% and injection pressure of 82.7 MPa. As can be seen in this figure, an increase in melt temperature from 260 to 288^{o}C caused considerable increase in the fatigue life of the material. Hold pressure had negligible influence on fatigue life of the material at both melt temperatures.

Figure 4 also shows that considerable increase in fatigue life was achieved by increasing the melt temperature from 260 to 288^{o}C. In Figure 4, the mold temperature was 49^{o}C, the injection speed was 36% and the injection pressure was 103.4 MPa. Two different hold pressures are included in Figure 4. It appears that hold pressure also had a relatively small effect at the higher melt temperature of 288^{o}C just as it was at the lower melt temperature of 260^{o}C.

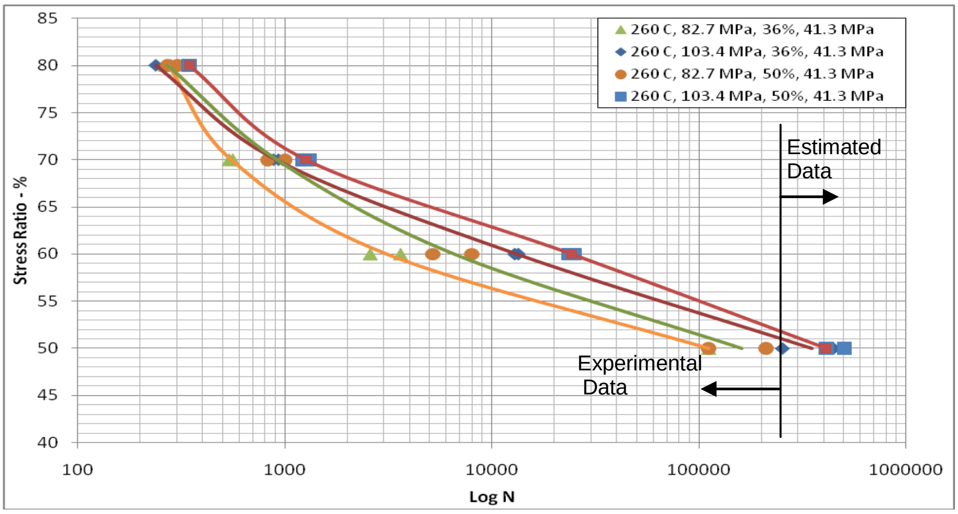

Figure 2. S-N curves at two different injection pressures (82.7 and 103.4 MPa) and two different injection speeds (36 and 50%), all at the same melt temperature of 260°C, mold temperature 49°C and hold pressure of 41.3 MPa.

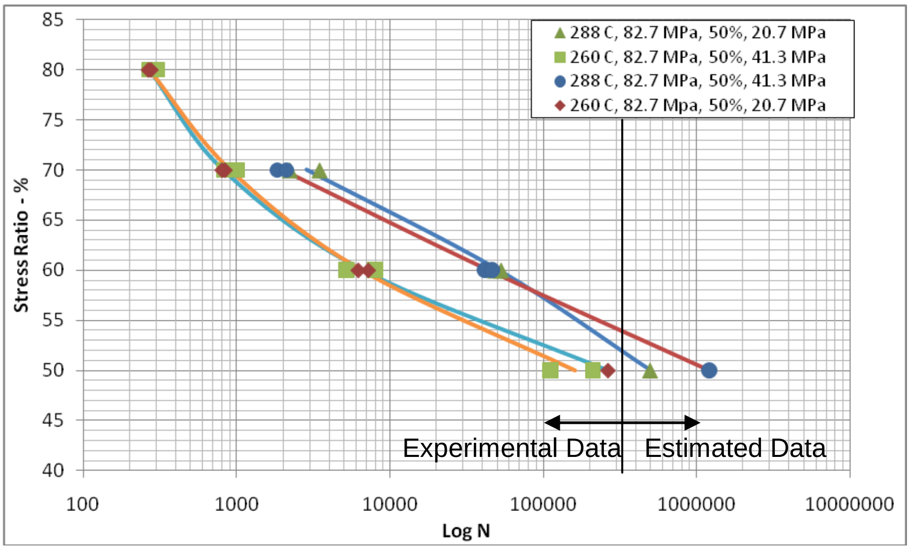

Figure 3. S-N curves at two different melt temperatures (260°C and 288°C) and two different hold pressures (20.3 and 41.3 MPa), all at the same injection pressure of 82.7 MPa, mold temperature of 49°C and injection speed of 50%

Figure 5 compares the effect of mold temperature and hold pressure at the lower melt temperature of 260°C and higher injection pressure and injection speed of 103.4 MPa and 50%, respectively. In Figure 5, it can be observed that mold temperature had a significant effect on the fatigue life of the material. The higher the mold temperature, the longer was the fatigue life. Hold pressure had very little effect on the fatigue performance of the material.

Figure 6 compares the effect of mold temperature and hold pressure at a melt temperature of 288°C and higher injection pressure and injection speed of 103.4 MPa and 50%, respectively. From the figure, it can be observed that neither mold temperature nor hold pressure have any significant effect on fatigue life of the material at the higher melt temperature of 288°C.

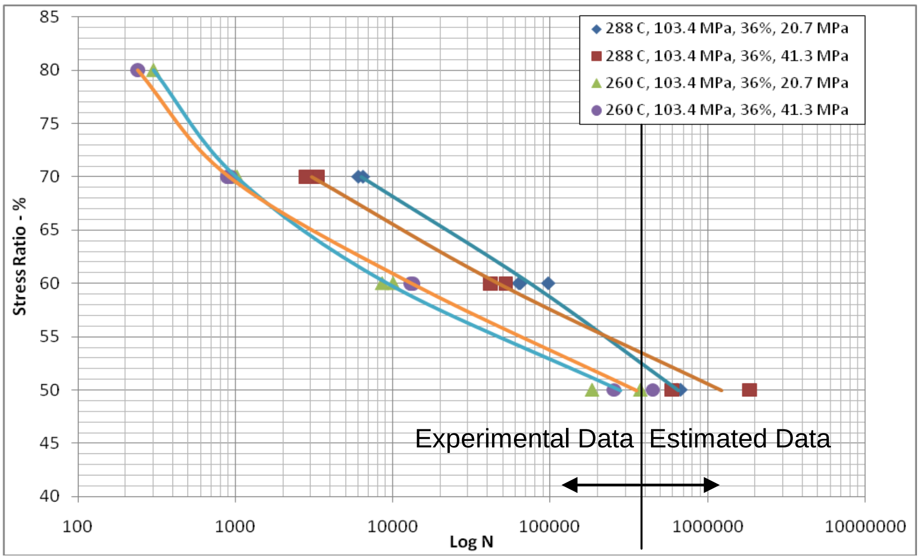

Figure 4. S-N curves at two different melt temperatures (260°C and 288°C) and two different hold pressures (20.3 and 41.3 MPa), all at the same injection pressure of 103.4 MPa, mold temperature of 49°C and injection speed of 36%

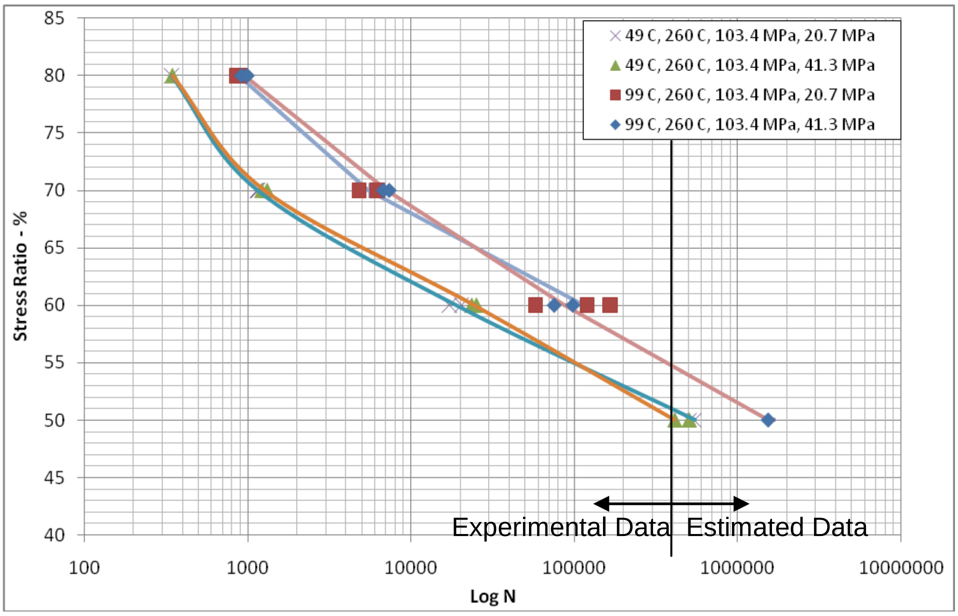

Figure 5. S-N curves at two different mold temperatures (49°C and 99°C) and two different hold pressures of 20.7 MPa and 41.3 MPa, all at the same injection pressure of 103.4 MPa, melt temperature of 260°C and injection speed of 50%

3.3 Fracture Surface Observations

Fracture surfaces of several fatigue specimens were observed under a scanning electron microscope. In most of the specimens, distinct skin-core morphology with various degrees of fiber orientations in the skins and core was observed. The core, located at the center of the specimen, is narrow strip of material in which fibers are oriented normal to the loading direction. In both Figures 7 and 8, the core is visible when the injection pressure was 82.7 MPa, but not when the injection pressure was 103.4 MPa. The melt temperatures for specimens in Figures 7 and 8 were 260 and 288°C, respectively, and the mold temperature was 49°C. Figure 9 shows the effect of mold temperature on core formation at a melt temperature of 288°C. Here, the core can be seen to be larger and the fiber orientation to be slightly more random when the mold temperature was 49°C instead of 99°C.

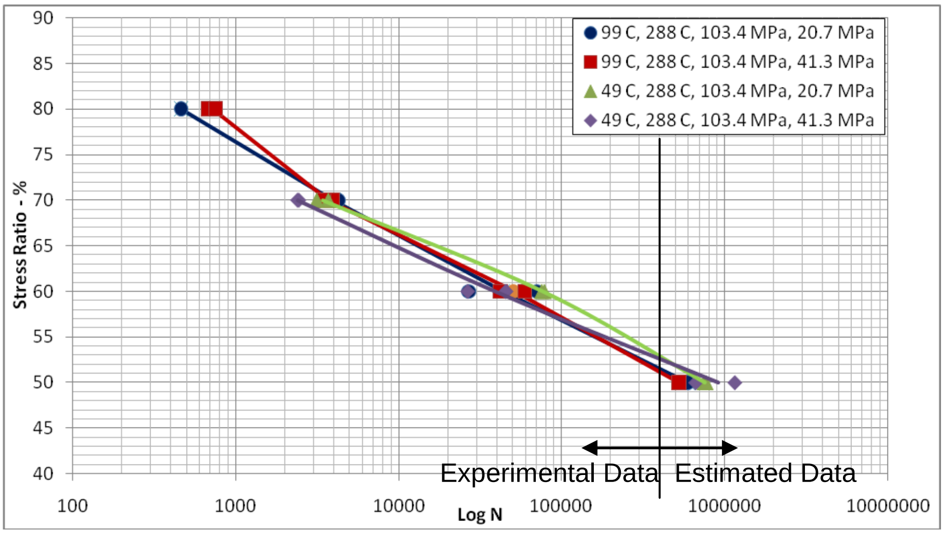

Figure 6. S-N curves at two different mold temperatures (49 °C and 99°C) and two different hold pressures of 20.7 MPa and 41.3 MPa, all at the same injection pressure of 103.4 MPa, melt temperature of 288°C and injection speed of 50%

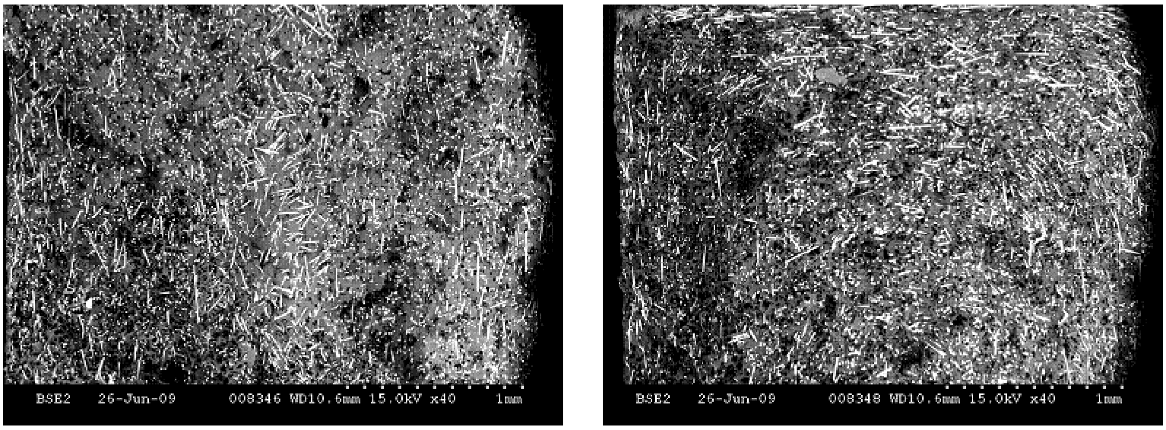

Figure 7. SEM photographs of fracture surfaces after fatigue tests (left: injection pressure 82.7 MPa and right: injection pressure 103.4 MPa, both at melt temperature of 260°C and mold temperature of 49°C)

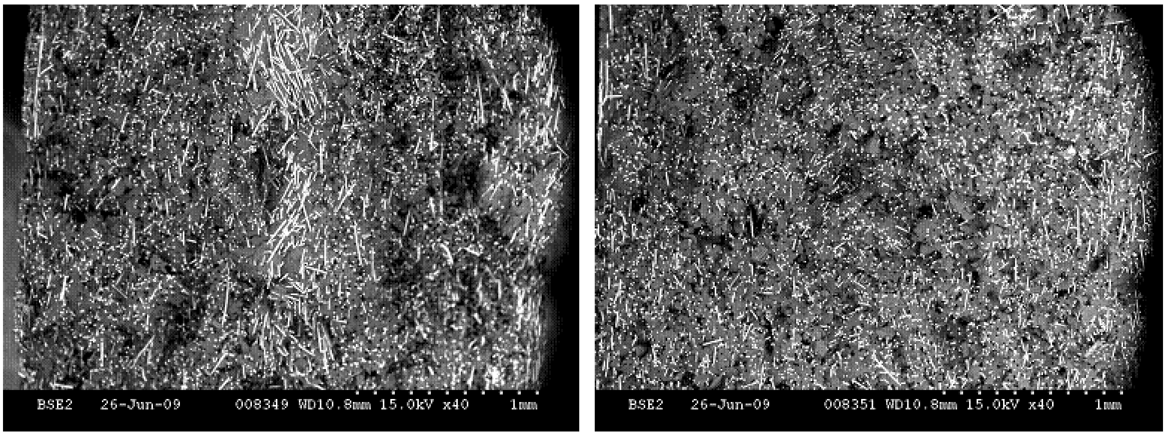

Figure 8. SEM photographs of fracture surfaces after fatigue tests (left: injection pressure 82.7 MPa and right: injection pressure 103.4 MPa, both at melt temperature of 288°C and mold temperature of 49°C)

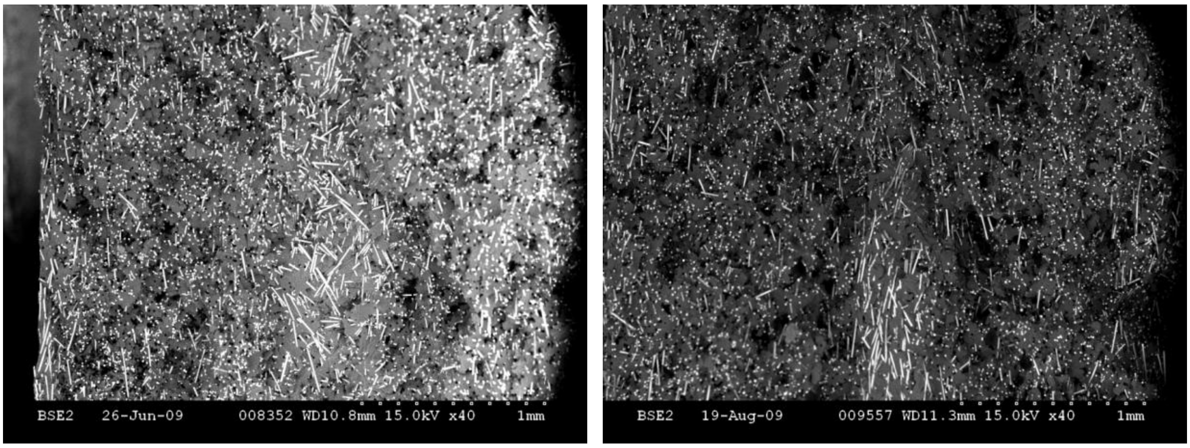

Figure 9. SEM photographs of fracture surfaces after fatigue tests (left: mold temperature of 49^{o}C, right: mold temperature 99 ^{o}C, both at melt temperature 288^{o}C, injection speed 50%, injection pressure 103.4 MPa and hold pressure 20.7 MPa)

3.4 Flow Simulation

Flow simulation was performed using Mold Flow software to determine the extent of fiber orientation in the specimen. The flow direction component a_{11} of the fiber orientation tensor was determined at three different locations at the mid-length of the specimen, as shown in Figure 10. As the specimen thickness was 3.2 mm, the distance between the measuring points in the thickness direction was 0.8 mm. The specimen length was 57 mm. It should be noted that a_{11} was measured at the mid-width, and as such it represents an average value over the entire width.

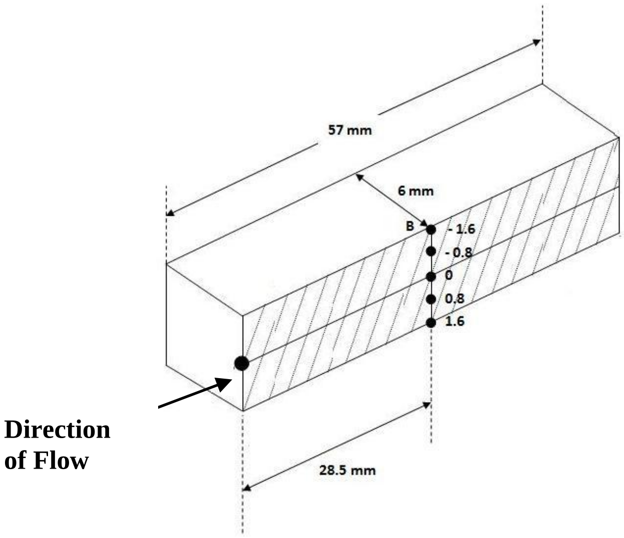

Figure 10. Locations at which the flow direction fiber orientation component a_{11} was measured

Figure 11 shows the a_{11} values at 49^{o}C mold temperature and at two different melt temperatures (260^{o}C and 288^{o}C). It can be noted in both figures that over a distance of 0.8 mm from either side of the centerline, the fiber orientation in the flow direction is lower than that over a distance of 0.8 mm from each surface. The lowest a_{11} value was at the center of the thickness. It can also be seen that a_{11} is lower at 288^{o}C than at 260^{o}C; thus at the higher melt temperature, the fibers throughout the thickness are much less oriented in the flow direction than at the lower melt temperature. Furthermore, at 288^{o}C, a_{11} is higher at measuring points -0.8 and 0.8 than at the surfaces, indicating that the surface fibers are less oriented in the flow direction than the sub-surface fibers. On the other hand, at 260°C, the fiber orientation is approximately uniform over a distance of 0.8 mm from each surface. The highest flow-direction fiber orientation on the surfaces was at 260°C melt temperature, 49°C mold temperature and 82.7 MPa injection pressure. Other observations that were made from the Mold Flow analysis are as follows:

(a) At lower melt temperature, lower injection pressure causes a higher fiber orientation in the flow direction and higher mold temperature causes lower fiber orientation in the flow direction. In general, hold pressure does not have much influence on fiber orientation in the flow direction.

(b) At higher melt temperature, higher injection pressure as well as higher hold pressure cause higher fiber orientation in the flow direction. Higher mold temperature also causes higher fiber orientation in the flow direction

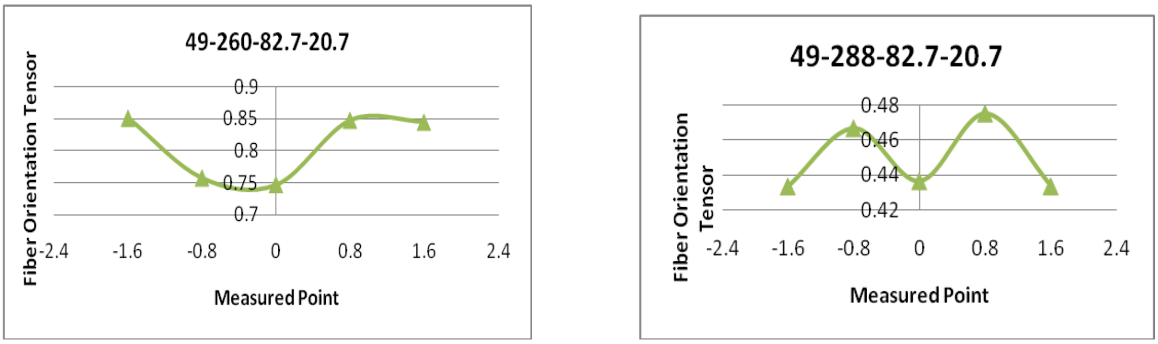

Figure 11. Examples of variation of flow direction fiber orientation component a_{11} across the thickness of injection molded specimens (left: melt temperature = 260°C and right: melt temperature = 288°C. For both, mold temperature = 49°C, injection pressure = 82.7 MPa and hold pressure = 20.7 MPa)

4 Conclusions

This study has shown that both melt temperature and mold temperature have significant effect on the fatigue properties of short glass fiber reinforced polyamide-6,6. Injection pressure also has a major influence. Injection speed and hold pressure have lower effects than the other three parameters. The fracture surface observations and flow simulations show complex nature of fiber orientation in the injection molded specimens, which depend on interaction of the injection molding parameters considered in this study.

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