FATIGUE PROPERTIES OF INJECTION MOLDED 33% E-GLASS FIBER REINFORCED POLYAMIDE- 6,6

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Abstract

Short fiber reinforced polyamide-6,6 is used in a variety of automotive components that are subject to vibrations over extended periods of time and are susceptible to fatigue failure. These components are usually injection molded and their performance depends on the injection molding conditions used for making them. The primary objective of the study was to determine the effects of a few key injection molding process parameters on the tensile and fatigue properties of 33wt% E-glass fiber reinforced polyamide-6,6. The process parameters selected were melt temperature, injection pressure, hold pressure and injection speed. It was observed that these process parameters had a greater influence on the fatigue properties than on the tensile properties. The melt temperature had the greatest effect followed by the injection pressure. Both hold pressure and injection speed had smaller, but significant effect on the fatigue life.

Introduction

Short glass fiber reinforced polyamide-6,6 (GF/PA-6,6) is used in many automotive components, such as air intake manifolds, steering column brackets and radiator fan blades [1]. When a vehicle is under operation, these components experience vibrations, and are therefore susceptible to fatigue failure. There had been several studies on the effect of test conditions on the fatigue properties of GF/PA-6,6. For example, Jia and Kagan [2] conducted tension–tension fatigue tests on GF/PA-6,6 at various test temperatures ranging from 40°C to 121°C and observed that its fatigue properties deteriorated with increasing test temperature. Another example of such a study that co-relates temperature and fatigue properties was a study by Handa et al. [3]. They studied the influence of cyclic frequency on temperature rise of the material. Cassado et al. [4] studied the surface roughness of the material after subjecting it to fatigue tests to determine the damage caused to the material due to such cyclic loading. They divided the fatigue response of the material into different stages and observed that crazing occurs in the material first, which then leads to pseudo-cracks. On being subjected to such loading even after initiation of such cracks, local instabilities produce a final crack and cause the material to fail.

In this work, the effects of several injection molding process parameters, such as melt temperature, injection pressure, hold pressure and injection speed, on the tensile and fatigue properties of a glass fiber reinforced polyamide-6,6 have been studied. Previously, we have reported the effects of orientation, presence of weld line and holes on the tensile and fatigue properties of this material [5]. This is a similar study in which the injection molding process parameters are considered. While the effects of injection molding process parameters on the tensile properties of GF/PA-6,6 and other polymers have been reported, their effects on fatigue performance have not been considered in the past.
The material investigated in the study was a 33 wt% E-glass fiber reinforced polyamide-6/6, which is available from DuPont under the trade name Zytel 70G33HS1L. A 90-ton Toyo injection molding machine was used to injection mold a dog-bone shaped tensile specimen, a rectangular flexural bar and a square plate in a 3-cavity mold (Figure 1). Each cavity was fitted with two end gates. One of the gates was switched off to injection mold the specimens that were used in this study. The pellets were dried at 80°C for a minimum of 2 hours before feeding them into the hopper of the injection molding machine.

The process parameters considered in this study included melt temperature, injection speed, injection pressure and hold pressure. Each process parameter was varied at two levels as shown in Table 1. The mold temperature was 49°C. The other process parameters, such as back pressure, suck back, hold speed, hold time, screw RPM and changeover position were kept constant throughout the injection molding experiments. Altogether 16 different injection molding conditions were considered and 10 specimens were molded for each condition. Out of these 10 specimens, three were tested in static tension and seven were tested in fatigue. A larger study in which mold temperature was also varied at two levels is under way and will be reported later.

Figure 1: Schematic of the 3-cavity mold used for injection molding tensile and fatigue specimens (4). Each cavity had two end gates with switch-off valves.
Table I: Injection molding process parameters studied

<table>
<thead>
<tr>
<th>Melt Temperature (°C)</th>
<th>260</th>
<th>103.4</th>
<th>288</th>
<th>103.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Pressure (MPa)</td>
<td>82.7</td>
<td>103.4</td>
<td>82.7</td>
<td>103.4</td>
</tr>
<tr>
<td>Injection Speed (% of the maximum speed)</td>
<td>36</td>
<td>50</td>
<td>36</td>
<td>50</td>
</tr>
<tr>
<td>Hold Pressure - 20.7 (MPa)</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Hold Pressure - 41.3 (MPa)</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

Tensile and fatigue properties of the injection molded material was determined using the dog-bone shaped specimens. The specimen dimensions were in accordance with the ASTM D-638 standard for testing tensile properties of plastic materials. Both tension and fatigue tests were conducted on an MTS servo-hydraulic testing machine. A strain rate of 0.05/min was applied on the specimen during the tension test. An extensometer was mounted at the mid-length of the specimen to determine the axial strain during the tension test. Stress-controlled cyclic fatigue tests were performed in tension–tension mode at room temperature (approximately 23°C). The ratio of the minimum cyclic stress to the maximum cyclic stress (R-ratio) was 0.1. Four different maximum cyclic stresses were considered, namely 50, 60, 70 and 80% of the average tensile strength for each injection molding condition. At least 2 specimens were tested at 60 and 70% stress levels and the number of specimens was adjusted at 50 and 80% stress levels, depending on the variation in fatigue life observed. All fatigue tests were conducted at a frequency of 2 Hz. Such a low frequency was selected to ensure fatigue failure and not thermal failure, since it has been reported fatigue specimens tend to exhibit thermal failure at higher frequencies. The fatigue tests were conducted up to 500,000 cycles or until failure, whichever occurred first.

Results and Discussions

Tensile Properties

Typical stress-strain diagrams obtained in tension tests are shown in Figure 2. The tensile properties obtained from each stress-strain diagram were the modulus (E) which was determined from the initial slope of the stress-strain diagram, tensile strength (TS) corresponding to the maximum stress observed, and strain at failure. These three tensile properties are plotted in Figure 3 at melt temperatures of 260 and 288°C. Each data point in this figure represents the average of three values. Since at each melt temperature, there were eight data points corresponding to two different injection pressures, two different injection speeds and two different hold pressures, they were purposely shifted horizontally to avoid overlapping. For all the specimens tested, the average tensile strength ranged from 128 MPa to 135 MPa, the average modulus ranged from 7.45 GPa to 8.5 GPa and the average strain at failure ranged from 3.6% to 6.5%. Thus, except for the strain at failure, the variation in tensile strength and modulus was relatively small.
Figure 2: Typical tensile stress-strain diagram of GF/PA-6,6 specimens. Note that the numbers corresponding to each curve show the melt temperature, injection pressure, injection speed and hold pressure, respectively.

It can be observed from Figure 3 that in general, all three tensile properties were lower at the higher melt temperature. At 260°C, the tensile strength was lower when higher injection pressure was used. At 288°C, there was a similar trend except at higher hold pressure and higher injection speed. At both melt temperatures, the highest tensile strength was obtained at lower injection pressure, lower injection speed and higher hold pressure. The effects of injection pressure on modulus and strain at failure were different, i.e., in general, higher values of these two properties were obtained with higher injection pressure. Another observation that can be made from Figure 3 is that injection speed and hold pressure had smaller effects on the tensile properties than melt temperature and injection pressure. Similar diagrams plotted against hold pressure and injection speed showed that these two process parameters did not have much influence on the tensile properties of GF/PA-6,6.
Figure 3: Tensile properties at two different melt temperatures (260 and 288°C)
Fatigue Properties

Fatigue S-N diagrams are shown in Figures 4-9. All of the specimens tested at 60, 70 and 80% stress levels failed at less than 100,000 cycles; however, most of the 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 they failed. Using the number of cycles to failure at 60% stress level, the expected number of cycles to failure 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.

\[ \frac{n_1}{N_1} + \frac{n_2}{N_2} = 1 \quad [1] \]

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 of the material at the same two stress levels. In this study, for the specimens that did not fail at 500,000 cycles at 50% stress ratio, \( n_1 \) is 500,000 and \( n_2 \) the number of cycles to failure of the same specimens at 60% stress ratio. \( N_1 \) is the expected fatigue life at 50% stress ratio, which is calculated from Eq. (1) and \( N_2 \) is the average fatigue life of the material at 60% stress ratio, which was determined by conducting the fatigue tests at 60% stress ratio.

In Figures 4-9, the S-N curves are drawn through the average cyclic life values at each stress level. Figure 4 shows four S-N curves at two different melt temperatures, 260 and 288°C, and two different hold pressures, 20.7 and 41.3 MPa, while the injection pressure and injection speed were 82.7 MPa and 36%, respectively. It can be observed from Figure 4 that melt temperature had a very significant effect on the fatigue life at all stress levels. In general, the higher the melt temperature, the higher was the fatigue life. Another observation that can be made from Figure 4 is that at each melt temperature, the higher hold pressure produced lower fatigue life. Similar observations can be made from Figures 5 - 7 in which the S-N curves are
Figure 5: S-N curves at two different melt temperatures (260 and 288°C) and two different hold pressures (20.7 and 41.3 MPa), all at the same injection pressure of 103.4 MPa and injection speed of 36%

Figure 6: S-N curves at two different melt temperatures (260 and 288°C) and two different hold pressures (20.7 and 41.3 MPa), all at the same injection pressure of 82.7 MPa and injection speed of 50%
Figure 7: S-N curves at two different melt temperatures (260 and 288°C) and two different hold pressures (2.03 and 41.3 MPa), all at the same injection pressure of 103.4 MPa and injection speed of 50% plotted for the same two melt temperatures and hold pressures, but at different injection pressures and injection speeds.

Figure 8 shows four S-N curves at the same melt temperature of 260°C and the same hold pressure of 41.3 MPa, but at two different injection pressures, 82.7 and 103.4 MPa, and two different injection speeds, 36% and 50%. It can be observed from this figure that higher injection pressure as well as higher injection speed produced longer life. However, the S-N curves plotted at the melt temperature of 288°C and hold pressure of 41.3 MPa (Figure 9) showed that at this higher melt temperature, higher injection pressure produced longer life at the lower injection speed, but did not have much effect at the higher injection speed.
Figure 8: 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 and hold pressure of 41.3 MPa

Figure 9: 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 288°C and hold pressure of 41.3 MPa
Fracture Surface Observation

The fracture surfaces of several fatigue specimens were examined under scanning electron microscope to determine the differences in fiber orientation and fiber-matrix bonding in the injection molded specimens. Each fracture surface exhibited a skin-core morphology with different degrees of glass fiber orientations in the core and in the skin. The relative size of the core and the skin varied with the processing condition. As the strength of glass fibers are far more superior than that of the polyamide-6,6 matrix, the greater the fiber orientation parallel to the loading direction, the higher will be strength of the short fiber reinforced polymer, since they are more effective in stress transfer than those oriented normal to the loading direction. The processing condition also affects the molecular orientation and crystalline morphology but it is the glass fiber orientation and bonding between the fiber and the matrix which play vital roles in determining the fatigue properties of the material.

Figure 10 shows the SEM photographs of the fracture surfaces of two fatigue specimens molded with two different injection pressures at 260°C melt temperature, 36% injection speed and 41.3 MPa hold pressure. Similarly, Figure 11 shows the fracture surfaces of two fatigue specimens molded with two different injection pressures at 288°C melt temperature, 36% injection speed and 20.7 MPa hold pressure.

Figure 10: SEM photographs of fracture surfaces after fatigue tests (Top: injection pressure = 82.7 MPa and bottom: injection pressure = 103.4 MPa, both at melt temperature of 260°C).
Figures 10 and 11 show a distinct core-skin morphology at the lower injection pressure, where the core contained fibers oriented normal to the flow direction which is surrounded by fibers oriented mostly in the flow direction. At the higher injection pressure, the presence of the core is less evident and the fiber orientation appears to be mostly in the flow direction. The greater amount of fiber orientation in the direction of flow is possibly the reason for higher tensile strength and fatigue life at higher injection pressure.

![Figure 11: SEM photographs of fracture surfaces after fatigue tests (Top: injection pressure = 82.7 MPa and bottom: injection pressure = 103.4 MPa, both at melt temperature of 288°C).](image)

Figure 11: SEM photographs of fracture surfaces after fatigue tests (Top: injection pressure = 82.7 MPa and bottom: injection pressure = 103.4 MPa, both at melt temperature of 288°C).

Figure 12 shows the SEM photographs of fracture surfaces at higher magnification. Both photographs show that the polymer surrounding the fibers underwent significant ductile deformation along the fracture path. It can also be observed from this figure that at lower injection pressure of 82.7 MPa, there was a weaker fiber-matrix bonding, causing debonding at the interface. At higher injection pressure of 103.4 MPa, there appears to be better bonding between the fibers and the matrix. The greater fiber-matrix bond strength may also have contributed to higher fatigue life at higher injection pressure. Further studies are being conducted to examine this effect.
Figure 12: SEM photographs of fracture surfaces after fatigue tests (Left: injection speed = 36%, injection pressure = 82.7 MPa and right: injection speed = 50%, injection pressure = 103.4 MPa, both at melt temperature of 260°C).

Conclusions

The effects of melt temperature, injection pressure, hold pressure and injection speed on the tensile and fatigue properties of an injection molded short E-glass fiber reinforced polyamide-6,6 are reported in this paper. The effects of the four process parameters considered in this study were more significant on the fatigue life than on the tensile properties of the materials. Melt temperature and injection pressure had a greater effect on the tensile properties than hold pressure and injection speed. Similar to the tensile properties, melt temperature and injection pressure had a large effect on the fatigue life of this material, but hold pressure and injection speed also seem to have significant influence. Through the SEM studies, it was shown that higher injection pressure produced greater fiber orientation in the direction of flow and greater fiber-matrix bonding, both of which may have contributed to the better fatigue performance at higher injection pressure.

References