Chapter 4
Rheology and Processing Behaviour of Recyclable Short Nylon Fibre Reinforced Thermoplastic Composites

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Chapter 4
Rheology and Processing Behaviour of Recyclable Short Nylon Fibre Reinforced Thermoplastic Composites

Part A. Rheology and processing behaviour of recyclable short nylon fibre reinforced polypropylene composites

4a.1 Introduction

The incorporation of short fibres to thermoplastics and elastomers to achieve cost reduction [1] and improvement in mechanical properties has become increasingly important in recent years. The rheological behaviour of such composites is important for selecting the processing parameters to fabricate products. A number of investigations on the rheological behaviour of short fibre reinforced thermoplastics and elastomers have been reported [2-5]. Usually, the incorporation of short fibres in thermoplastics and elastomers increases the melt viscosity and may make processing more difficult. The melt viscosity of glass fibre filled polyethylene (PE) and PP was studied by Becraft and Metzner [6-7] and it was found that there is a significant increase in viscosity with fibre loading at low shear rates and little change in viscosity at higher shear rates. A decrease in melt viscosity as a result of the incorporation of short fibres is also reported [8-11].

4a.2 Experimental

The melt rheological measurements were carried out using a Shimadzu capillary rheometer (50kN) at different plunger speeds from 1-500 mm/min. The capillary used had a length of 40mm and diameter 1mm at an entry angle of 90°. The measurements were carried out at two different temperatures viz. 180 and 220 °C.
4a.3 Results and discussion

4a.3.1 Effect of fibre loading and shear rate on viscosity

Figures 4a.1 & 4a.2 show the variation of viscosity of PP composites [12] with shear rate and fibre loading at 180 and 220 °C. These curves are typical of pseudoplastic materials, which show a decrease in viscosity with increasing shear rate. All the systems investigated have been found to obey the power law relationship viz.

\[ \eta = k \gamma^{n-1} \]

where, \( n \) is the power law index and \( k \) the consistency index.

![Figure 4a.1 Variation of melt viscosity with shear rate at 180 °C](image-url)
Rheology and processing behaviour of recyclable short nylon fibre reinforced polypropylene composites

Figure 4a.2 Variation of melt viscosity with shear rate at 220 °C

In the case of nylon fibre/PP composites viscosity increases with fibre loading. The two possible factors affecting the viscosity are 1) increased fibre matrix-interaction that increases the viscosity and 2) increased wall slip due to the presence of longitudinally oriented fibres along the wall/melt interface that decreases the viscosity. In the case of unmodified polypropylene, fibre may stick to the walls due to low fibre matrix adhesion and this may increase the viscosity.

4a.3.2 Effect of matrix modification on melt viscosity

Figures 4a.3 & 4a.4 show the effect of interface modification on the viscosity of nylon fibre reinforced polypropylene composites at 180 and 220 °C. From the figure it is clear that the viscosity of the composite decreases. This is interesting since there is a marginal increase in molecular weight upon modification. In the case of modified polypropylene the fibre matrix interaction is high and hence more fibres may adhere to surface of the matrix resulting in more wall slip and hence viscosity reduction.
Figure 4a.3 Variation of melt viscosity with shear rate at 180 °C

Figure 4a.4 Variation of melt viscosity with shear rate at 220 °C
4a.3.3 Effect of temperature on melt viscosity

The effect of temperature on the viscosity of polymers is important as the polymers are subjected to significant temperature gradient during processing. Figure 4a.5 & 4a.6 show the variation of melt viscosity of the composite at 180 °C and 220 °C at different shear rates. The viscosity of the composite decreases with increase in temperature.

![Figure 4a.5 Variation of the melt viscosity of Nylon fibre/PP composites with shear rate at 180 °C and 220 °C](image-url)
Figure 4.6 Variation of the melt viscosity of Nylon fibre/ SMA-g-PP composites with shear rate at 180 °C and 220 °C
4a.3.4 Flow behaviour index (n’)

The dependence of flow behaviour index on fibre content and interface modifications at two different temperatures viz. 180 and 220 °C are shown in Table 4a.1.

**Table 4a.1 Flow behaviour index value for Nylon fibre/PP composite**

<table>
<thead>
<tr>
<th>Material</th>
<th>Flow behaviour index (n’)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at 180°C</td>
</tr>
<tr>
<td>0% Fibre + PP</td>
<td>0.549</td>
</tr>
<tr>
<td>10% Fibre + PP</td>
<td>0.574</td>
</tr>
<tr>
<td>20% Fibre + PP</td>
<td>0.689</td>
</tr>
<tr>
<td>30% Fibre + PP</td>
<td>0.752</td>
</tr>
<tr>
<td>10% Fibre + SMA-g-PP</td>
<td>0.538</td>
</tr>
<tr>
<td>20% Fibre + SMA-g-PP</td>
<td>0.684</td>
</tr>
<tr>
<td>30% Fibre + SMA-g-PP</td>
<td>0.743</td>
</tr>
</tbody>
</table>

Non-Newtonian pseudoplastic materials have n’ values less than unity. In the case of Nylon fibre /PP composite the n’ values were found to be less than unity indicating pseudoplastic nature of the system. It is found that for all the mixes flow behaviour index decreases as temperature increases indicating that the melt becomes more non-Newtonian in nature as the temperature is increased.
4a.3.5 Die swell behaviour of nylon fibre reinforced polypropylene composite

The increase in the diameter of the extrudate as it comes out of the capillary is known as die swell. This phenomenon occurs as a result of the orientation of polymer molecules as they are sheared while passing through the die of extruder. As the melt comes out of the die, reorientation and recovery of the molecules occur and these lead to die swell.

a) Effect of shear rate

Figure 4a.7 shows the die swell behaviour of PP, nylon fibre/PP composite and nylon fibre/SMA-g-PP composite at different shear rates at a constant temperature of 180 °C. There is a decrease in the die swell ratio upon the addition of fibre. At the same fibre loading the die swell ratio increases with shear rate. These observations are in agreement with results reported in literature. In the case of short fibre composites, during flow through the capillary, orientation of polymer molecules and fibres takes place. As the composites come out of the capillary, polymer molecules retract by recoiling effect. Further, the behaviour shows that the fibres remain as fillers at ordinary processing temperatures.

The unequal retractive forces experienced by the two components of the composite can lead to redistribution of fibres. Since the molecules at the periphery undergo maximum deformation, the retractive forces on these molecules will also be higher. Thus retractive force, is mainly responsible for the die swell of short fibre filled composite.

![Figure 4a.7 Variation of die swell ratio of nylon fibre/PP composites at different shear rates at 180 °C](image-url)
b) Effect of temperature

Figure 4a.8 gives the variation of die swell ratio of PP, nylon fibre/PP composite and nylon fibre/SMA-g-PP composite at different shear rates at a constant temperature of 220 °C. There is an increase in the die swell ratio upon the addition of 20 per cent fibre loading. At the same fibre loading the die swell ratio increases with shear rate. At this higher temperature the nylon fibre also gets melted. As the blends come out of the capillary polymer molecules retract by recoiling effect. Therefore the die swell ratio increases.

Figure 4a.8 Variation of die swell ratio of nylon fibre /PP composites at different shear rates at 220 °C.
4a.3.6 Activation energy

The variations of melt viscosity with reciprocal of absolute temperature of nylon fibre/PP composites at two different shear rates 1333 and 6666 s\(^{-1}\) are reported (Table 4a.2). Activation energies were calculated from the Arrhenius plots of viscosity and temperatures at different shear rates. From the table it can be observed that the activation energy of flow of the composites increases with modification at the lower shear rate, while there is not much increase at the higher shear rate. This is in confirmation with our observations that activation energy of flow increases with modification due to the resulting molecular weight increases, but at higher shear rates the increase is not pronounced due to alignment of molecules in the shear field.

Table 4a.2 Activation energies (kJ/mol) of flow of nylon fibre/PP composites at two shear rates

<table>
<thead>
<tr>
<th>Sample</th>
<th>Activation energy (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at 1333 (s(^{-1}))</td>
</tr>
<tr>
<td>0% Fibre + PP</td>
<td>9.4</td>
</tr>
<tr>
<td>10% Fibre + PP</td>
<td>10</td>
</tr>
<tr>
<td>20% Fibre + PP</td>
<td>11</td>
</tr>
<tr>
<td>30% Fibre + PP</td>
<td>11.5</td>
</tr>
<tr>
<td>10% Fibre + SMA-g-PP</td>
<td>14.8</td>
</tr>
<tr>
<td>20% Fibre + SMA-g-PP</td>
<td>15.7</td>
</tr>
<tr>
<td>30% Fibre + SMA-g-PP</td>
<td>15</td>
</tr>
</tbody>
</table>
Part B. Rheology and processing behaviour of recyclable short nylon fibre reinforced high density polyethylene composites

4b.1 Introduction

This section describes the rheological behaviour of nylon fibre/HDPE and nylon fibre/SMA-g-HDPE composite.

4b.2 Experimental

The melt rheological measurements were carried out using a Shimadzu capillary rheometer (50kN) at different plunger speeds from 1-500 mm/min. The capillary used had a length of 40 mm and diameter 1mm at an angle of entry 90°. The measurements were carried out at two different temperatures viz. 180 and 220 °C. The rheological measurements were also made on Haake torque rheometer since it represents real processing equipment.

4b.3 Results and discussion

4b.3.1 Effect of fibre loading and shear rate on viscosity

Figures 4b.1 & 4b.2 show the variation of viscosity of HDPE composites with shear rate and fibre loading at 180 °C and 220 °C. The viscosity of the nylon fibre/HDPE composites increases with fibre loading as in the case of nylon fibre/PP.
Rheology and processing behaviour of recyclable short nylon fibre reinforced high density polyethylene composites

Figure 4b.1 Variation of melt viscosity with shear rate at 180 °C

Figure 4b.2 Variation of melt viscosity with shear rate at 220 °C
4b.3.2 Effect of matrix modification on melt viscosity

Figures 4b.3 & 4b.4 show the effect of modification on the viscosity of nylon fibre/HDPE composites at 180 and 220 °C. From the figure it is evident that the viscosity of the composite decreases with modification as observed in the case of nylon fibre/HDPE composite.
4b.3.3 Effect of temperature on melt viscosity

Figures 4b.5 & 4b.6 show the variation of melt viscosity of the composite at 180 and 220 °C at different shear rates. The viscosity of the composite decreases with temperature as expected.

Figure 4b.5 Variation of the melt viscosity of nylon fibre/HDPE composites with shear rate at 180 °C and 220 °C
4b.3.4 Flow behaviour index ($n'$)

The dependence of flow behaviour index on fibre content and interface modifications at two different temperatures viz. 180°C and 220°C is shown in Table 4b.1. In the case of nylon fibre/HDPE composite the $n'$ values were found to be less than unity indicating pseudoplastic nature of the system same as in the case of nylon fibre/PP composite.
Table 4b.1 Flow behaviour index value for Nylon fibre/HOPE composite

<table>
<thead>
<tr>
<th>Material</th>
<th>Flow behaviour index (n') at 180 °C</th>
<th>Flow behaviour index (n') at 220 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% Fibre + HDPE</td>
<td>0.290</td>
<td>0.250</td>
</tr>
<tr>
<td>10% Fibre + HDPE</td>
<td>0.468</td>
<td>0.45</td>
</tr>
<tr>
<td>20% Fibre + HDPE</td>
<td>0.699</td>
<td>0.679</td>
</tr>
<tr>
<td>30% Fibre + HDPE</td>
<td>0.676</td>
<td>0.656</td>
</tr>
<tr>
<td>10% Fibre + SMA-g- HOPE</td>
<td>0.510</td>
<td>0.401</td>
</tr>
<tr>
<td>20% Fibre + SMA-g- HDPE</td>
<td>0.673</td>
<td>0.342</td>
</tr>
<tr>
<td>30% Fibre + SMA-g- HDPE</td>
<td>0.708</td>
<td>0.447</td>
</tr>
</tbody>
</table>

4b.3.5 Die swell behaviour of nylon fibre reinforced HDPE composite

a) Effect of shear rate

Figure 4b.7 shows the die swell behaviour of HDPE, Nylon/HDPE composite and Nylon/SMA-g- HDPE composite at different shear rates at a constant temperature of 180 °C. There is a decrease in the die swell ratio upon the addition of fibre. At the same fibre loading the die swell ratio increases with shear rate. These observations are same as in the case of nylon fibre/PP composite.

Figure 4b.7 Variation of die swell ratio of Nylon fibre/HDPE composites at different shear rates at 180 °C
Figure 4b.8 Variation of die swell ratio of Nylon fibre/HOPE composites at different shear rates at 220 °C

b) Effect of temperature

Figure 4b.8 gives the variation of die swell ratio of HDPE, Nylon/ HDPE composite and Nylon/SMA-g- HDPE composite at different shear rates at a constant temperature of 220 °C. There is an increase in the die swell ratio upon the addition of fibre as observed in the case of nylon fibre/PP composite.

4b.3.6 Activation energy

The variation of melt viscosity with reciprocal of absolute temperature of nylon fibre/PP composites at two different shear rates 1333 and 6666 s⁻¹ are reported. Activation energies of HDPE, nylon fibre/ HDPE composite and nylon fibre/SMA-g- HDPE composite are given in Table 4b.2. Activation energies were calculated from the Arrhenius plots of viscosity and temperatures at different shear rates. As in the case of the nylon fibre/PP composite, the activation energy increases with chemical modification of the matrix. However the increase is not very pronounced at higher shear rate.
Table 4b.2 Activation energies (kJ/mol) of flow of nylon fibre/HDPE composites at two shear rates

<table>
<thead>
<tr>
<th>Sample</th>
<th>Activation energy (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at 1333 (s⁻¹)</td>
</tr>
<tr>
<td>0% Fibre + HDPE</td>
<td>0.90</td>
</tr>
<tr>
<td>10% Fibre + HDPE</td>
<td>2.23</td>
</tr>
<tr>
<td>20% Fibre + HDPE</td>
<td>1.66</td>
</tr>
<tr>
<td>30% Fibre + HDPE</td>
<td>2.08</td>
</tr>
<tr>
<td>10% Fibre + SMA-g-HDPE</td>
<td>2.77</td>
</tr>
<tr>
<td>20% Fibre + SMA-g-HDPE</td>
<td>3.66</td>
</tr>
<tr>
<td>30% Fibre + SMA-g-HDPE</td>
<td>3.25</td>
</tr>
</tbody>
</table>

4b.4 Rheological measurements using Torque Rheometer

4b.4.1 Effect of fibre loading and shear rate (rpm) on viscosity (torque)

Figure 4b.9 shows the plot of log torque Vs log rpm for various fibre loading. The family of straight lines obtained is parallel showing that the power law indices for the parent polymers and their composites are more or less the same. The rheological interpretation of the measurements was based on the analysis of Blyler and Daane. Goodrich and Porter considered the torque rheometer measuring head as two adjacent rotational viscometers with irregular concentric cylinders [13-19]. They succeeded in converting torque rheometer data into fundamental rheological units for materials that exhibit Newtonian viscosity. Blyler and Daane extended this work to Non-Newtonian materials and derived the equation

\[ M = C(n)K \eta^n \]

where M is the torque, K and n are parameters of the famous power law equation.
Table 4b.3 shows the power law indices (n) for different fibre loading and these n values can be used for predicting the behaviour of the composites at lower shear rate. The constant n value agrees with the parallel straight line obtained in the log melt viscosity Vs log rpm plot.

![Graph showing flow curves from torque rheometer](image)

**Figure 4b.9 Flow curves from torque rheometer**

**Table 4b.3 Power law index values for Nylon fibre/HDPE composites**

<table>
<thead>
<tr>
<th>Power law index (n value)</th>
<th>10% Fibre + HDPE</th>
<th>20% Fibre + HDPE</th>
<th>30% Fibre + HDPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.26</td>
<td>0.21</td>
<td>0.23</td>
</tr>
</tbody>
</table>

4b.4.2 Effect of matrix modification on melt viscosity

Figure 4b.10 shows the plot of log torque Vs log rpm for various fibre loading in which the matrix is modified. The torque value remains almost constant. Table 4b.4 shows the power law indices (n) for different fibre loading and these n values can be used for predicting the behaviour of the composites at lower shear rate.
Rheology and processing behaviour of recyclable short nylon fibre reinforced high density polyethylene composites

Figure 4b.10 Flow curves from torque rheometer

Table 4b.4 Power law index values for Nylon fibre/ SMA-g-HDPE composites

<table>
<thead>
<tr>
<th>Power law index (n value)</th>
<th>10% Fibre + SMA-g-HDPE</th>
<th>20% Fibre + SMA-g-HDPE</th>
<th>30% Fibre + SMA-g-HDPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.39</td>
<td>0.25</td>
<td>0.31</td>
</tr>
</tbody>
</table>

4b.4.3 Energy required for processing

The energy required for processing the composites at different rpm for a period of 8 min is given in Table 4b.5. The energy needed is found to be increasing with the fibre loading and also with the increase in rpm as expected.
Table 4b.5 Energy required for processing of Nylon fibre/HDPE composites at different rotor speeds

<table>
<thead>
<tr>
<th>Rotor speed (r.p.m)</th>
<th>Energy required (kJ) for processing at different fibre content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10% Fibre</td>
</tr>
<tr>
<td>40</td>
<td>15.3</td>
</tr>
<tr>
<td>60</td>
<td>29.1</td>
</tr>
<tr>
<td>80</td>
<td>36.6</td>
</tr>
<tr>
<td>100</td>
<td>41.2</td>
</tr>
</tbody>
</table>
Chapter 4
Rheology and Processing Behaviour of Recyclable Short Nylon Fibre Reinforced Thermoplastic Composites

Part C. Simulation studies of recyclable short nylon fibre reinforced polypropylene composites.

4c.1 Introduction

In the continuing demands for materials with improved performance including reduced weight, increased strength, faster productivity and lower cost, thermoplastics and thermoset polymers are both classes of materials that cannot be ignored. The former have thus attracted much interest for structural applications. Polypropylene is one of the most commonly used thermoplastic polymers. Fibre reinforced composite materials have recently been adapted to improve upon the mechanical properties of plastic materials. Accordingly, PP reinforced with synthetic fibres is now widely used in automobile applications.

Reinforced thermoplastics are commonly manufactured by injection moulding, a process which has the benefits of a short production cycle, yielding excellent surfaces and the ease of moulding complex shapes. However, mixing short fibres with the polymer matrix can greatly change the mechanical properties, in a manner strongly dependent on the orientation and distribution of the fibres. Selecting and identifying injection moulding process parameters that affects proper fibre orientation, is thus of major concern to the plastics industry.

The orientation of short fibres in injection moulding has been investigated. Some researchers have focused on the simulation of fibre orientation Hirari et al. [20] predicted the distribution of fibre orientation in thin injection moulded parts, for a flow of molten resin considered to exhibit two dimensional isothermal properties. Greene et al. [21-23] also developed computer programs to predict the two dimensional fibre orientations in thin, composite parts. Other researchers have been interested in three dimensional simulation of fibre orientation. Friedl et al. [24] proposed a model to predict three dimensional fibre orientation distribution in injection mouldings.

Bay and Tucker [25] simulated fibre orientation in simple injection moulding using a three-dimensional second rank tensor function. The finite element method was employed by Kabenemi et al. [26] to calculate the flow behaviour and fibre orientation during the filling of injection moulded parts.
Most studies on fibre orientation address the correlation of processing conditions with both fibre orientation and mechanical properties in different materials, to help in optimizing processing conditions to yield desired properties. Wilson et al [27] examined the effects of moulding variables on the mechanical properties of short fibre reinforced thermoplastic polyurethane; the properties were evaluated both parallel and perpendicular to the polymer flow. Bright and Darlington, and Xavier et al. [28-29] similarly examined the influence of injection moulding parameters on the fibre orientation distribution, and the mechanical properties of glass fibre reinforced polypropylene. The observed mechanical properties were explained with reference to fibre orientation. Barbosa and Kenny [30] statistically elucidated the relationships among processing conditions, fibre distribution and mechanical behaviour. The correlation between fibre orientation and mechanical properties for other materials was considered by Delpy and Fischer [31].

4c.2 Experimental

The standard tensile specimens (ASTM D 638) were moulded in a semiautomatic reciprocating injection moulding machine, with a maximum injection pressure of 60 MPa. Mold Flow Software was used to predict the parameters like fill time, tensile modulus along the principal direction, air traps, and the fibre orientation and distribution in the polymer matrix. The properties feed to the software are listed below (Table 4c.1).
Simulation studies of recyclable short nylon fibre reinforced polypropylene composites

Table 4c.1 Physical properties of PP and nylon fibres

<table>
<thead>
<tr>
<th>Property</th>
<th>PP</th>
<th>Nylon Fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melt flow rate</strong></td>
<td>Melt Flow Index of PP : 20 g/10 min (230 °C/2.16kgf)</td>
<td></td>
</tr>
<tr>
<td><strong>Thermal properties of PP</strong></td>
<td>Processing temperature : 200 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific heat : 3064 J/kg-C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heating/Cooling rate : -0.1667 °C/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity : 0.15 W/m-C</td>
<td></td>
</tr>
<tr>
<td><strong>PVT properties of PP</strong></td>
<td>Melt Density : 0.738 g/cc</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solid Density : 0.907 g/cc</td>
<td></td>
</tr>
<tr>
<td><strong>Mechanical properties of PP</strong></td>
<td>Elastic Modulus (First Principal Direction) : 900 MPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poisson’s Ratio : 0.392</td>
<td></td>
</tr>
<tr>
<td><strong>Properties of nylon fibre</strong></td>
<td>Density : 0.98 g/cc</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Heat : 1047 J/Kg-C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal Conductivity : 0.24 W/m-C</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 4c

4c.3 Results and discussion

4c.3.1 Fill Time

Figure 4c.1 shows the mold filling characteristics of 30% nylon fibre/PP composite obtained by simulation with an approximate fill time of 2 sec (as observed experimentally). The actual fill times obtained by simulation are shown in the figure 4c.2. Similar results are obtained with other composites having fibre contents of 10, 20 and 40%. It may be observed that the fill time marginally increases with fibre content obviously due to the increased resistance to flow with increase in fibre content.
4c.3.2 Tensile Modulus along Principal Direction

Figure 4c.3 shows the simulated result of tensile modulus along the principal direction of nylon fibre/PP composite. The predicted maximum modulus is 1535 MPa for 30% fibre loading. Experimental value observed is 1400 MPa (Chapter 3a), which is within the experimental limits.
Fibre orientation is a very important parameter in deciding the mechanical properties of composite. In injection-molded composites, the fibre alignment (or orientation) show a layered nature, and are affected by the filling speed, the processing conditions and the material behavior, plus the fibre aspect ratio and concentration. Figure 4c.4 shows the simulated result of average orientation of nylon fibres in a 30 % nylon fibre/PP composite. The maximum orientation of the fibres is along the principal direction where maximum strength is expected. There can be a significant variation in mechanical properties with different mold geometry and fibre content.
4c.3.4 Air Trap

An air trap is an air or gas bubble that has been trapped by converging flow fronts or trapped against the cavity wall. This causes a surface blemish on the part. In our specimen the air traps are found to be at the corners of the sample and hence the mechanical properties are not much likely to be adversely affected (Figure 4c.5).
The volumetric shrinkage result is a 3D flow analysis result from mold flow simulation. Volumetric shrinkage should be uniform across the whole part to reduce warpage. The maximum shrinkage observed for 30% nylon fibre/PP composites is 5% as shown in Figure 4c.6.
4c.3.6 Bulk Temperature (End of Filling)

Bulk temperature is used to indicate the weighted average temperature across the thickness. It represents the energy that is transported through a particular location. The temperature of polymer melt changes not only with time and location, but with thickness during the entire injection-molding cycle as well. From the figure it is observed that the maximum temperature occurs in the melt injecting zone as expected. In the case of nylon fibre/PP composites it should be ensured that the high temperature zones do not affect the reinforcing fibres. From the figure 4c.7 maximum temperature recorded is 200 °C and hence it may be concluded that the temperatures involved are within the limits.
4c.3.7 Time to Freeze

The Freeze time result is generated from a 3D flow analysis, and shows the time for the part to cool down to ejection temperature, measured from the start of the cycle. The freeze time at several locations varies across the surface of the specimen as shown in Figure 4c.8.
4c.3.8 Temperature at flow front

Figure 4c.9 shows the temperature of the polymer flow front at the end of the analysis. It predicts that there will not be any short shot or material degradation since the temperature is neither too high nor too low.
The sink index shows potential shrinkage due to a hot core. It is calculated for each location at the instant when local pressure has decayed to zero during the packing stage, and reflects how much material is still in molten form and left unpacked. As can be observed from the Figure 4c.10, potential areas where sink marks can occur are at the upstream end of the sample where the packing may not be efficient to compensate the shrinkage. Also the runner area is prone to shrinkage since there is no packing to compensate shrinkage in this area. However this does not affect the dimensional stability of the sample.
Frozen layer fraction shows the thickness of the frozen layer as a fraction at the end of the filling phase. Frozen layer thickness has very significant effects on the flow resistance. The viscosity exponentially increases with decreasing temperature. The thickness of the flow layer is also reduced as the thickness of the frozen layer increases. The least frozen layer thickness is shown at the extreme end of the sample (Figure 4c.11).
Conclusions

The following conclusions can be drawn from the rheological behaviour of nylon fibre/PP and nylon fibre/HDPE composites.

Viscosity increases with fibre content. However, this effect is significant only in the lower shear range. In the higher shear range the increase in viscosity is only marginal when the fibre content increases from 10 to 30%. The viscosity further reduces with chemical modification. At higher shear rate the viscosity of modified composite is close to that of matrix polymer.

As expected, the melts are pseudoplastic in nature and the viscosity decreases with increase in temperature. It can be observed that the composite becomes less pseudoplastic with the addition of fibres. The strongest pseudoplastic nature is obtained at 220°C when the composite gets converted into a blend.

The die swell behaviour is also widely different at the two processing temperatures. At 180°C the die swell decreases with addition of fibre while at 220°C the die swell increases with fibre addition.

The activation energy of flow increases with fibre addition and matrix modification. However, the activation energy marginally decreases with increase in shear.

The moldflow software can be used for determining the fibre orientation, tensile modulus, temperature profile, fill time, shrinkage etc.
Simulation studies of recyclable short nylon fibre reinforced polypropylene composites

References


14. "Measuring the fusion rate of rigid PVC dry blends" International Plastics


