Supporting Information

Insight into the Directional Thermal Transport of Hexagonal Boron Nitride Composites

Mahdi Hamidinejad\textsuperscript{a}, Azadeh Zandieh\textsuperscript{a}, Jung H. Lee\textsuperscript{a}, Justine Papillon\textsuperscript{b}, Biao Zhao\textsuperscript{a}, Nima Moghimian\textsuperscript{c}, Eric Maire\textsuperscript{b}, Tobin Filleter\textsuperscript{a*}, and Chul B. Park\textsuperscript{a*}

\textsuperscript{a} Department of Mechanical and Industrial Engineering, University of Toronto, 5 King’s College Road, Toronto, Canada M5S 3G8

\textsuperscript{b} University of Lyon, INSA de Lyon, MATEIS UMR CNRS 5510, Bât. Saint Exupery, 23 Av. Jean Capelle, F-69621 Villeurbanne, France

\textsuperscript{c} NanoXplore Inc., 25 Boul. Montpellier, Saint-Laurent, QC, H4N 2G3

\textsuperscript{*}Corresponding Authors’ Information: E-mail: filleter@mie.utoronto.ca; park@mie.utoronto.ca
Address: 5 King’s College Road, Toronto, Ontario M5S 3G8, Canada
S1. Cellular microstructure

Figure S1 shows that cells are smaller in the skin regions of the porous composites and they gradually become larger in the core region. This can be attributed to higher melt strength due to the lower melt temperature in the skin region, where cellular growth is suppressed. Figure S2 shows the SEM images of HDPE/10.2 vol% hBN and HDPE/19.7 vol% hBN composites.

Figure S1. (a) X-ray tomography (top view) of the skin and core regions of the porous HDPE/10.2 vol% hBN composites; (b) the cell sizes of porous HDPE/10.2 vol% hBN composites in the skin and core regions
Figure S2. SEM micrographs of the skin and core regions for the solid and porous (with 10% porosity) HDPE/10.2 vol% hBN and HDPE/19.7 vol% hBN composites.
S2. Thermal conductivity

The thermal conductivity variations as a function of the filler content for two different porosities (i.e. 10% and 20%) are presented in Figure S3. As shown in Figure S3, the generation of a microcellular structure increased the through-plane thermoconductivity of the solid HDPE/hBN composites up to 478.5%, while their in-plane conductivity decreased by maximum 68.2%.

Figure S3. (a) The through-plane thermal conductivity ($K_\perp$) and; (b) the in-plane thermal conductivity ($K_{\parallel}$) of solid and porous (10% and 20% porosity) HDPE/hBN composites as a function of the hBN content.

Figure S4 shows the Differential Scanning Calorimetry (DSC) data on the HDPE/hBN composites.

Figure S4. (a) Differential Scanning Calorimetry (DSC) data of the HDPE/hBN composites
**S3. Sample preparation**

A TDS-20 twin-screw extruder (screw diameter =22 mm; L/D=40) was used to produce HDPE/40 wt.% hBN masterbatch by melt mixing. The temperature profile was set to 180-220°C with a rotational speed of 45 rpm and a throughput of 5 kg.h$^{-1}$. The HDPE/hBN composites with various hBN concentrations were then produced by diluting the HDPE/40 wt.% hBN masterbatch with neat HDPE by mixing in a twin-screw extruder (with diameter of 27 mm and L/D: 40). An injection molding machine (Arburg Allrounder 270/320C,) equipped with MuCell® technology (Trexel, Inc., Woburn, Massachusetts) with 30-mm diameter screw was used to fabricate the solid and porous HDPE/hBN composites. The mold cavity dimensions were 132 × 108 × 3 mm. More detailed information about the mold used in this research was reported by Lee et al. $^1$. Two different types of HDPE/hBN composite, solid injection molded (Solid) and foam injection molded (Porous), were fabricated. The porosity in the porous samples was controlled by partially filling the mold.

The solid HDPE-hBN composites were fabricated using regular injection molding process without SCF-treatment (using N$_2$ as the SCF) and physical foaming. For the porous composites, the MuCell module was used to inject 0.4 wt.% N$_2$ at its supercritical state in the barrel. After treating the HDPE-hBN with the SCF, the mold cavity was partially filled with the polymer/hBN/N$_2$ mixture. The porosity of the samples is controlled by partial-filling of the mold volume. The utilized processing parameters in this work are summarized in Table S1. The conventional and foam injection molding processes are schematically presented in Figure S5.
Table S1. Processing parameters used in injection molding of solid and porous composites

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Solid</th>
<th>Porous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt temperature (°C)</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>Barrel pressure (MPa)</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Screw speed (rpm)</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Metering time (s)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Injection flow rate (cm³s⁻¹)</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Mold temperature (°C)</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Pack/hold pressure (MPa)</td>
<td>30</td>
<td>N/A*</td>
</tr>
<tr>
<td>Pack/hold time (s)</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>Cooling time (s)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Gas injection pressure (MPa)</td>
<td>N/A</td>
<td>24</td>
</tr>
<tr>
<td>N₂ content (wt.%)</td>
<td>N/A</td>
<td>0.4</td>
</tr>
<tr>
<td>Degree of foaming (porosity) (%)</td>
<td>N/A</td>
<td>10, 20</td>
</tr>
</tbody>
</table>

*Not Applicable

The disk-shape solid and porous HDPE/hBN composites were cut from the injection-molded parts at a distance of 100 mm from the cavity gate as shown in Figure S5. The samples with a 20 mm diameter × 3 mm thickness were used to measure the thermal conductivity, the dielectric constant, and dielectric loss.
**Figure S5.** The schematic of regular and foam injection molding processes, the injection molded parts and the location of cut samples.
S4. Thermal conductivity measurement

The thermal conductivity of the HDPE-hBN composites was measured using the transient hot disk method. Measurements were conducted based on the ISO/DIS 22007-2.2 standard. In this technique, an electrically conductive double spiral disk-shape nickel foil sensor acts as a heater to increase the samples’ temperature (Figure S6). The sensor also works as a dynamic thermometer which records temperature change in the sample as a function of time. The measurement requires two identical pieces of samples and the sensor is placed between two samples (Figure S6). The generated heat pulse dissipates into the samples at a rate which depends on the thermal transport properties of the samples. By recording the temperature with respect to the time response in the sensor, the thermal conductivity can be calculated. For a theoretical standpoint, the interested readers are referred to research works presented by Gustafsson \(^{R2}\), Gustavsson et al. \(^{R3}\), Miller et al. \(^{R4}\) and He \(^{R5}\).

![Figure S6](attachment:image.png)

**Figure S6.** (a) Samples’ dimensions; (b) the schematic of the ISO/DIS 22007-2.2 setup for measuring the thermal conductivity using TPS 2500

Based on the ISO/DIS 22007-2.2 standard, Gustafsson \(^{R2}\), Gustavsson et al. \(^{R3}\), Miller et al. \(^{R4}\) and He \(^{R5}\), the transient plane source method (TPS) is suitable for measuring the thermal conductivity of both isotropic and anisotropic materials. Figure S7 shows the heat penetration (probing depth) during thermal conductivity measurement using Anisotropic Measurement Module.
Figure S7. The heat penetration (probing depth) during thermal conductivity measurement using Anisotropic Measurement Module for solid and porous HDPE/hBN composites.

References:


