Nanotenology applied to textile among students of materials engineering for skill development

Ricardo Rodrigo Ramos Cecci  
SENAI CETIQT

Adriano Alves Passos  
SENAI CETIQT

Nathan Riany Valério Albino  
SENAI CETIQT

Daniel da Silva Vicente  
SENAI CETIQT

Ademir Severino Duarte  
SENAI CETIQT

Maria Inês Bruno Tavares  
IMA/UFRJ
Objective: In aiming to obtain fibers with enhanced thermal and mechanical properties, graphene based textile fibers with 144 filaments were developed using an approach in which the PP/GnP (polypropylene/graphene nanoplatelets) nanocomposite was employed as conductive material in a fiber with circular cross-section geometry. Method: The kinetics of thermal degradation was evaluated by the Broido method using thermogravimetric analysis (TGA). Results: Activation energy was enhanced from 260.6 kJ.mol$^{-1}$ to 337.4 kJ.mol$^{-1}$ compared to the neat PP. GnP increased the thermal stability of the PP, slowing its degradation by thermal depolymerization. Furthermore, the degree of crystallization declined as the GnP content increased, reducing the tenacity of the yarn, but improving its elastic modulus from 91.9 to 95.9 cN/tex, being a promising alternative to produce smart textiles. Conclusion: In conclusion, it has been confirmed that GnP loading up to 1% (w/w) can be incorporated into polypropylene by melt spinning and that the resulting nanocomposite fibers are suitable for several applications in the textile industry.

INTRODUCTION

The successful development of conductive textile fibers allows electronic devices to be integrated into the textile structures, giving rise to so-called smart textiles. As part of their development, conductive fibers can modify the traditional protective function of clothing, and can be an infrastructure for communication, providing the generated information to monitor areas such as health and emotions (FERREIRA; FERREIRA; PAIVA, 2013).

Besides that, industrial demand for electrically conductive textile fibers has grown also for other applications in the fields of mechanical (PICCIANI et al., 2016), thermal (SEYEDIN et al., 2015) and chemical sensors (SOROUDI; SKRIFVARS, 2012), photovoltaic devices (SCAFFARO; MAIO; TITO, 2012), electrostatic charge dissipation (LI et al., 2007), shielding of electromagnetic radiation (DEOGAONKAR; BHAT, 2015), wave absorption in the microwave range (BEDELOGLU et al., 2010), wireless devices (SAINI; SHARMA; AKODIA, 2016), flexible rechargeable batteries (SAINI; CHOUDHARY, 2013), radar-undetectable textiles (HAJI; RAHBAR; SHOUSHTARI, 2014) and data transfer on clothing (SHYAMKUMAR et al., 2014).

Several manufacturing methods have been studied in order to increase the conductivity of synthetic textile fibers; the most used are coating (ALI et al., 2017), electrospinning (ZHANG et al., 2016), wet spinning (REDLICH et al., 2014) and melt spinning (CHEN et al., 2016). However, an important challenge when developing conductive fibers is how to reach high conductivity, without losing mechanical and thermal properties.

Among these manufacturing methods, melt mixing followed by melt spinning is a preferred route because mixing nanofillers in the solid state is more efficient in the dispersion and exfoliation of thin sheets of graphene nanoplatelets (GNPs) in a polymer matrix. Besides that, no further preparation routes using dangerous solvents are required and that common extruders can be used (NILSSON et al., 2013).

Many researchers are working with melt spinning technique to obtain fibers with better performances. Chatterjee, Nüesch, and Chu (2013) dispersed graphene nanoplatelets on polyamide 12 (PA 12) matrix by melt spinning. They observed by wide-angle X-ray diffraction (WAXD) analysis that the degree of crystallinity of the PA 12/GnP nanocomposite fibers increased with the incorporation of nanofillers due to nucleation effects. The stress-strain curves (σ-ε) showed an improvement in the mechanical properties of the PA 12/GnP fibers, such as the increase of elastic modulus, yield strength, tensile strength and tenacity, compared to pristine polyamide fiber, indicating a good dispersion of graphene in the polymer matrix.

The incorporation of graphene into polymers not only gives rise to nanocomposites and fibers with improved electrical, magnetic and mechanical properties, but also with higher thermal stability (KALANTARI et al., 2015). These properties can be changed dramatically...
with the addition of small amounts of graphene due to the combination of their dimensionality, structure, atomic thickness and high aspect ratio (JI et al., 2016).

Due to these unique features, graphene has many applications in the field of textile fibers, of greatest interest being UV protection, supercapacitors, photocatalytic activity, hydrophobicity, antibacterial effect and high electrical conductivity (JAVED et al., 2014).

Graphene-based polymer nanocomposites fibers show a large increase in electrical conductivity with increasing graphene concentration up to the electrical percolation threshold (FAN et al., 2012). It is a critical value of filler concentration at which the polymer matrix transits from insulator to conductor. Above this point, several conduction paths are formed in the material for the conduction of electrons. Thus, the electrical conductivity of the nanocomposite grows abruptly by several orders of magnitude and often shows a saturation plateau (MA et al., 2010). Therefore, one of the challenges is to lower the electrical percolation threshold in order to obtain the best conductivity with the lowest filler content. For example, Nilsson et al. (2013) produced fibers based on conductive PP/GnP nanocomposites by melt spinning. At 20% (w/w) GnP, the fibers reached the percolation threshold, showing a conductivity of $7.9 \times 10^{-6} \text{S.cm}^{-1}$.

To obtain an enhanced performance of the fibers, which means a uniform dispersion of graphene in the polymer matrix without restacking, special attention must be paid. The first problem is the aggregation of the graphene sheets (ZHANG et al., 2017). The second is the random distribution of the graphene sheets in the nanocomposite (FAN et al., 2012).

In order to solve the first problem, the strategy to produce the fibers involved two steps. The direct inclusion of graphene in the polymer melt of polypropylene uses a twin-screw extruder (melt mixing) for first homogenization. During nanocomposite formation, shear forces are useful for breaking up agglomerates, promoting the dispersion of the graphene sheets. Thereafter, the resulting nanocomposite was then melt spun to fiber filaments, drawn and wound (melt spinning). The second problem is mitigated with the drawing of the fiber. This is expected because extension causes the polymer chains to be more orderly together with graphene sheets. The aim of this work is to study the effect of graphene on thermal, mechanical, and morphological properties of polypropylene fibers.

**METHOD**

**Materials**

Isotactic H 201 grade polypropylene (PP) was supplied by Baskem S.A. This grade has good melt stability, high melt index (MI: 20 g/10 min), normal molecular weight distribution and 0.905 g/cm³ of density. Graphene nanoplatelets (GnP-5), grade M with average particle
diameters of 5 μm were supplied by XG Sciences, Michigan, United States of America. The average thickness of Grade M GnP particles is approximately 6 nm, a typical surface area about 120-150 m²/g and 2.2 g/cm³ of density.

**Preparation of PP/GnP Nanocomposites**

The graphene nanoplatelets were physically mixed with the PP pellets and added to the feed hopper of an interpenetrating co-rotational twin screw extruder (L/D = 30) coupled to a pelletizer, model Compounder ZK25T, Dr. Collin, Germany. The concentration range of GnP was 0 to 1.0% w/w. The same route without GnP was performed to obtain the reference PP. The temperature profile used during extrusion ranged from 120 to 240 °C. The gear pump speed was 20 rpm, the melt pressure was 80 bar and the screw speed automatically adjusted between 45 and 50 rpm.

**Preparation of PP/GnP Fibers**

The PP/GnP graphene nanoplatelets were added to the feed hopper of an extruder aforementioned and then spun to fibers in a spinning system (CMF 100, Dr. Collin, Germany). The fibers were continuously cooled with compressed synthetic air to a minimum temperature of 25 °C. Then, the fibers were hot drawn using the 4-roll (Godet-type) roller heated up to 110 °C. The drawing ratio of 2 was used for all fibers. Finally, the drawn fibers were wound in continuous filament by means of a winder on a cardboard core with an inner and outer diameter of 94 mm and 104 mm, respectively.

The matrix used was a spinneret of circular cross section with diameter of 115 mm containing 144 capillaries (Ø = 0.17 mm). The screw rotation and melt spinning temperature profile were the same as that used to obtain nanocomposites. The same route without GnP was performed to obtain the reference PP fiber. Examples of the as-spun bobbins are shown in Figure 1.
Characterization

Morphology of the pure PP and PP/GnP fibers was examined by using a scanning electron microscope (SEM). The images were taken using a Hitachi TM3030 microscope of the Electronic Microscopy Laboratory (CETEM/UFRJ), operated at 15 kV in backscattered electrons (BSE) mode.

Optical microscopy was performed using polarized light microscopy Leica DM500 to visualize dispersion of GnP in the polypropylene fibers in the microscale.

Data from a dynamic TGA Q-500 (TA Instruments®) were plotted \( \ln \left( \ln \left( \frac{1}{1-\alpha} \right) \right) \) vs. \( \frac{1}{T} \) and the activation energy (Ea) was calculate by the slope of the - Ea/R curve, using Broido’s kinetic method (BROIDO, 1969). The heating rate was 10 °C. min\(^{-1}\), and the experiments were performed in a continuous nitrogen flow at a flow rate of 60 mL. min\(^{-1}\). The temperature was in the range 30-700 °C.

The degree of crystalline of pure PP fiber and PP/GnP nanocomposite fibers were determined by X-ray diffraction (XRD) using a Rigaku Ultima IV X-ray 4,000 diffractometer (Cu K\(\alpha\) radiation \( \lambda = 1.5406 \) Å). Samples were scanned in 2\(\theta\) ranges from 2°-60° at a rate of 0.05°/s. Measurements were recorded at every 0.05°. The XRD patterns were deconvoluted with the aid of Fityk software. The diffractograms were adjusted with Gaussian function, using 6 Gaussian function profiles to describe the crystalline peaks and 1 profile to represent the amorphous halo of the non-crystalline fraction. Then, the calculation of the sample’s crystallinity percentage was obtained by the following relation of areas, according to Eq. (1).

\[
\lambda_{c, x} = \frac{\sum Ca}{\sum (Ca + Aa)} \times 100
\]

(1)

where, Ca is the crystalline area and Aa is the amorphous area.

Tensile strength was determined according to testing standard ISO 2062:2009 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2009) using a Universal Testing Machine (UTM), Instron 5900 R, with a load cell of 500 N. A cross head speed
of 50 mm.min\(^{-1}\) was used and the gauge length was set at 50 mm. Ten samples of each fiber were tested to determine the stress-strain curve. The fiber yarn count was based on three yarn samples of 1,000 m each, which were weighed according to ISO 13214 standard (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 1994).

The fibers tenacity was calculated from the stress-strain curves by normalizing the breaking force against yarn count, according to Eq. (2).

\[
\gamma = \frac{F}{Y_C} \tag{2}
\]

where \(\gamma\) is tenacity (cN/tex), \(F\) is force recorded at break (cN) and \(Y_C\) is the yarn count (tex).

The elastic modulus (\(E\)) of the fibers was determined by the slope of the tenacity-elongation between the initial linear elastic regions, where Hooke’s Law is valid, according to Eq. (3).

\[
E = \frac{\gamma}{\varepsilon} \tag{3}
\]

where \(E\) is the elastic modulus (cN/tex), \(\gamma\) is the tenacity in the elastic regime of the tenacity-elongation curve (cN/tex) and \(\varepsilon\) is the elongation in the elastic regime of the tenacity-elongation curve (%). At least, mean and standard deviation were calculated from the obtained results.

### RESULTS AND DISCUSSION

#### Morphological Analysis

Optical microscopy was used to check the quality of the GnP dispersion and distribution in PP matrix. Figure 2 shows a selection of the respective optical images of the PP/GnP nanocomposite fibers. Although light microscopy images have shown that GnP is evenly distributed over the PP matrix, there are areas with aggregates of GnP in the PP/GnP fibers.

*Figure 2. Optical micrographs of PP/GnP nanocomposite fibers with different GnP loadings, 20× magnification.*
The arrows in Figure 2 indicate the aggregation more clearly. The number and size of aggregations increase with increasing GnPs content in the fibers. Similar aggregation has been previously reported for PP/GnP nanocomposite fibers by Kalantari et al. (2015).
It is observed that pure PP fibers have a flat, smooth and homogeneous surface. The incorporation of GnP resulted in the appearance of protuberances and heterogeneities on the surface of PP/GnP fibers.

In addition, by increasing the concentration of GnP in the fibers, the surface roughness became greater. The individual platelets are present in the stacked shape on the surface of the fibers, where the black arrows show stacks of nanoplatelets perpendicular to the surface, while the white arrows point to the nanoplatelets parallel to the fiber surface. The estimated average diameter of the fiber filaments is about 19 µm.

Based on Figures 2 and 3, it can be deduced that most GnP are well dispersed, while some GnP are aggregated in the fiber. Individual graphene nanoplatelets have greater affinity to themselves rather than polymer matrix, resulting in the lack of homogeneous dispersion of the nanoplatelets. As the filler loading increases, the melt spinning process becomes gradually less effective in dispersing of GnP, due to the higher viscosity of nanocomposites melts and the lack of enough shear force to break GnP aggregates during extrusion (CHATTERJE; NÜESCH; CHU, 2013; KALANTARI et al., 2015).
GnP easily aggregates together to form bundles because of van der Waals forces and interplanar $\pi-\pi$ interactions among them. The additional lack of interfacial bond between polymer matrix and GnPs can cause agglomeration, making their dispersion in polymer matrices even more challenging (KALANTARI et al., 2015; ZHANG et al., 2017).

**Thermal Analysis**

Thermal stability is a key factor for the characterization of textile fibers, as temperature may limit its use in technical applications. Many researches have shown that incorporation of GnP can substantially increase the thermal stability of polymer-based textile fibers (WEISE et al., 2019) due to the high aspect ratio and sheet structure of graphene. PP-based fibers are included which degrade exclusively by random homolytic cleavage of chains in the absence of oxygen (CHEN et al., 2016).

For the PP/GnP nanocomposite fibers, the addition of GnP induced the overall thermal stabilization of the system, as well as assisted in residue formation after thermal decomposition. Thermal degradation behaviors are compared in the weight loss (TGA) and derivative weight loss (DTG) curves of Figs. 4 and 5, respectively. The thermogravimetric data are summarized in Table 1.

<table>
<thead>
<tr>
<th>GnP content (%)</th>
<th>$T_{\text{onset}}$ (°C)</th>
<th>$T_{10}$ (°C)</th>
<th>$T_{90}$ (°C)</th>
<th>$T_{\text{offset}}$ (°C)</th>
<th>Residue (%)</th>
<th>$T_{\text{peak}}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure PP 0.0%</td>
<td>390</td>
<td>408</td>
<td>473</td>
<td>478</td>
<td>0</td>
<td>463 ± 2</td>
</tr>
<tr>
<td>0.25%</td>
<td>419</td>
<td>435</td>
<td>485</td>
<td>490</td>
<td>1</td>
<td>475 ± 2</td>
</tr>
<tr>
<td>0.50%</td>
<td>422</td>
<td>439</td>
<td>486</td>
<td>490</td>
<td>1</td>
<td>474 ± 2</td>
</tr>
<tr>
<td>0.75%</td>
<td>423</td>
<td>440</td>
<td>488</td>
<td>493</td>
<td>2</td>
<td>473 ± 2</td>
</tr>
<tr>
<td>1.00%</td>
<td>427</td>
<td>444</td>
<td>490</td>
<td>495</td>
<td>2</td>
<td>477 ± 2</td>
</tr>
</tbody>
</table>

Source: Authors.

The onset and the end set of thermal degradation temperature were determined from the intersection of two tangents, before and after the thermal event, according to ASTM E2550 (AMERICAN SOCIETY FOR TESTING AND MATERIALS, 2011). $T_{10}$ and $T_{90}$ are the temperatures at which 10% and 90% degradation occurs, respectively. $T_{\text{peak}}$ is the maximum decomposition temperature of the DTG curves. The remaining fraction of nonvolatile material left at 600 °C is called residue.
Evidently, each of the degradation temperatures increased with increasing GnP content in fibers. However, this increase in degradation temperatures was not linearly proportional. For example, the change of $T_{\text{onset}}$ from pure PP (0% GnP) to PP/GnP fiber (1.0%) was about 37 °C, and $T_{10}$ was about 36 °C. While for the final temperatures, the influence of GnP was smaller, as $T_{\text{offset}}$ and $T_{90}$ both increased just 17 °C.

Similar trend was observed by Bafana et al. (2017), who found that for PP/GnP nanocomposites, the effect of graphene on improving thermal stability was more pronounced at the onset of degradation. The hypothesis is that in the early stages of thermal decomposition, GnP could shift decomposition to higher temperatures due to the barrier effect promoted by them when well dispersed, so-called the tortuous path. This effect creates a diffusive control in the matrix, so retards the gas permeation and the escape of volatile degradation products. The intensity of this effect is strongly affected by the aspect ratio, dispersion and orientation of the graphene sheets, by the graphene interface with the polymer matrix and by the polymer crystallinity (CUI; KUNDALWAL; KUMAR, 2016).

In the final stages of degradation, stacked graphene layers can accumulate heat, which could accelerate the decomposition process, resulting in a reverse thermal stability.

In addition, the higher decomposition temperature of GnP compared to PP matrix led to higher residue formation, still maintaining an additional fraction of the polymer. For example, the residue found for pure PP (0% GnP) was 0%, and for PP/GnP fiber (1.0%) was 2.0%. While GnP is extremely stable up to 600 °C, they do not have enough oxygen atoms to destabilize their structure.
Figure 5. DTG curves of pure PP fiber and PP/GnP nanocomposite fibers. Heating rate: 10 °C.min⁻¹.

It can be seen from the DTG curves (Figure 5) that pure PP fiber decomposes in a single step, presenting a low intensity broad peak with maximum decomposition velocity centered at 463 °C. While for all GnP concentrations, fibers also showed only one decomposition stage with a narrower and more intense peak. Therefore, it can be assumed that the process became faster at the beginning of fibers mass loss when compared to pure PP fiber. This observation aligns the above interpretation, i.e., GnP increases the overall thermal stability of the system, but can accelerate the degradation in the final stages, since T_{peak} temperatures are closer to T_{90} and T_{offset} temperatures (Table 1).

Degradation Kinetics Analysis

The study of the degradation kinetics was performed by applying Broido’s kinetic method (BROIDO, 1969) for allowing calculating the activation energy (Ea) of degradation with only one TGA curve. In contrast, the kinetic methods of Kissinger, Horowitz-Metzger, Coats-Redfern, Ozawa-Flynn-Wall, Doyle and Friedman use three or more TGA experiments with different heating ramps (CHETANA; SIDDARAMAIAH; RAMAPPA, 2005).

Thus, in a dynamic TGA the samples were heated with a linear heating rate of 10 °C.min⁻¹ and from the obtained data it was possible to plot ln[ln(1/(1-α))] vs. the reciprocal of the absolute temperature 1/T and to calculate the activation energy (Ea) by the slope of the line of -Ea/R.

Figure 6. graphically shows the Broido model applied to the thermal degradation of pure PP and its PP/GnP nanocomposite fibers in the temperature range where the decomposition is linear (from 458 to 474 °C). The kinetic data and the activation energies are summarized in Table 2.
Figure 6. Graphical representation of ln[ln(1/(1-α))] versus 1/T from the Broido model equation for degradation of pure PP and PP/GnP nanocomposite fibers. Heating rate: 10 °C.min⁻¹.

![Graphical representation](image)

Source: Authors.

Table 2. Kinetic data of thermal degradation of pure PP and PP/GnP nanocomposite fibers obtained by Broido method. Activation energy, Ea; coefficient of determination, r²; line slope, -Ea/R; and gas constant, R (8.314 J.mol⁻¹K⁻¹).

<table>
<thead>
<tr>
<th>GnP content (%)</th>
<th>Ea (kJ·mol⁻¹)</th>
<th>r²</th>
<th>-Ea/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure PP 0.0%</td>
<td>260.6</td>
<td>0.999</td>
<td>-31.35</td>
</tr>
<tr>
<td>0.25%</td>
<td>336.3</td>
<td>0.999</td>
<td>-40.45</td>
</tr>
<tr>
<td>0.50%</td>
<td>338.0</td>
<td>0.999</td>
<td>-40.65</td>
</tr>
<tr>
<td>0.75%</td>
<td>328.2</td>
<td>0.999</td>
<td>-39.48</td>
</tr>
<tr>
<td>1.0%</td>
<td>337.4</td>
<td>0.999</td>
<td>-40.58</td>
</tr>
</tbody>
</table>

Source: Authors.

The coefficient of determination (r²) values showed a good fit of the Broido model to describe the thermal degradation of pure PP and PP/GnP fibers. The addition of 1.0% (w/w) graphene nanoplatelets in the PP increased the activation energy required for the decomposition of the fiber by 29.5%, confirming its positive effect on the thermal stability of PP. This effect may be related to the good dispersion of GnP in the PP matrix and to a specific interaction between PP and GnP the increase decomposition activation energy and slow degradation on the sample surface due to better heat distribution within GnP-based nanocomposite fibers. The Eₐ found for pure PP by the Broido method is in agreement with that found in the literature. Arranz-Andrés, López, and Benavente (2017) studied the thermal degradation of isotactic PP via TGA and determined the activation energy of 226 kJ.mol⁻¹ by Friedman method, under nitrogen atmosphere and heating rates of 2, 5, 10, 20 and 30 °C.min⁻¹.

In conclusion, the presence of GnP improved the thermal stability of the polypropylene due to the higher activation energy required for decomposition.
Tensile Analysis

Tensile analysis was carried out to determine the influence of GnP on the mechanical properties of the PP melt-spun fibers. Each sample was tested 10 times, allowing the statistical average and standard deviation to be calculated (Table 3). Figure 7 shows the effect of filler loading on elastic modulus and tenacity of PP/GnP nanocomposite fibers.

Figure 7. Elastic modulus and tenacity of PP/GnP nanocomposite fibers at different filler loading.

With the addition of GnP considerable improvement could be recorded in the mechanical properties of the nanocomposite fibers. An important improvement of 4.35% could be observed for elastic modulus with the inclusion up to 0.75% (w/w) GnP, as compared with the pure PP fiber, but over this concentration threshold, the elastic modulus drops dramatically. This might be due to the excess GnP and the emergence of aggregates at high concentrations as supported by our optical analysis data. Aggregates lead to more brittle behavior. Higher GnP content also increases the brittleness as the polymer-GnP adhesion gets weakened (CHATTERJEE; NÜESCH; CHU, 2013). In this case, the lower stress transfer due to low interfacial adhesion as the GnP loading grows, results in a lower nanocomposite fiber elastic modulus. A good dispersion could be a dominating factor in this threshold, because huge aggregates within the fiber cause voids that are created by interfacial debonding. They are not stable and grow to a size where initial crack occurs (AHMAD; YOUNG; KINLOCH, 2015).

On the other hand, the tenacity of fibers with graphene is lower than that of pure PP fibers, i.e., the tenacity decreased as more graphene was incorporated. This might be due to the decreased degree of crystallinity supported by XRD analysis and the weak interfacial interaction between the GnP and PP matrix of the nanocomposite fibers. Therefore, the GnP acts as grain boundaries and perturbing agents in the fibers (WEISE et al., 2019), resulting in higher internal tension at lower strain rates and thus less force was required for fiber
rupture (Table 3). Figure 8 shows the effect of filler loading on elongation at break of PP/GnP nanocomposite fibers.

Table 3. Yarn count and tensile strength data of pure PP and PP/GnP nanocomposite fibers.

<table>
<thead>
<tr>
<th>GnP content (%)</th>
<th>Degree of crystallinity* (%)</th>
<th>Yarn count (dtex)</th>
<th>Elastic modulus (cN·tex⁻¹) AVG</th>
<th>Elastic modulus (cN·tex⁻¹) STDEV</th>
<th>Tenacity (cN·tex⁻¹) AVG</th>
<th>Tenacity (cN·tex⁻¹) STDEV</th>
<th>Elongation at break (%) AVG</th>
<th>Elongation at break (%) STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure PP 0.0%</td>
<td>60.28</td>
<td>1,414</td>
<td>91.9</td>
<td>6.9</td>
<td>15.6</td>
<td>0.9</td>
<td>433.7</td>
<td>8.2</td>
</tr>
<tr>
<td>0.25%</td>
<td>56.10</td>
<td>1,474</td>
<td>93.0</td>
<td>6.7</td>
<td>13.1</td>
<td>1.3</td>
<td>402.6</td>
<td>6.4</td>
</tr>
<tr>
<td>0.50%</td>
<td>54.31</td>
<td>1,414</td>
<td>95.1</td>
<td>2.0</td>
<td>8.9</td>
<td>0.3</td>
<td>256.3</td>
<td>7.6</td>
</tr>
<tr>
<td>0.75%</td>
<td>52.62</td>
<td>2,080</td>
<td>95.9</td>
<td>3.4</td>
<td>8.4</td>
<td>0.8</td>
<td>165.1</td>
<td>5.1</td>
</tr>
<tr>
<td>1.00%</td>
<td>50.34</td>
<td>1,576</td>
<td>54.3</td>
<td>4.8</td>
<td>5.3</td>
<td>0.2</td>
<td>34.1</td>
<td>5.7</td>
</tr>
</tbody>
</table>

*Calculated from XRD data.

The incorporation of GnP in the polypropylene matrix resulted in a drastic decrease in the elongation at break of the nanocomposite fibers. The pure PP fiber exhibited the elongation at break of 433.7%, as nanocomposite fibers with GnP exhibited the elongation at break of 34.1%.

The reduction of elongation at break with increasing filler loading might be due to the decreased deformability of a rigid interface between the filler and PP matrix (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2009). When GnP loading was increased up to 1% (w/w), weaker regions between polymer-GnP interface were created. Since crack spreading is easier through the weaker interfacial regions, lower elongation was required for fiber rupture with increasing GnP loading. In conclusion, the nanocomposite fibers with GnP showed brittle fracture, whereas the pure PP fiber revealed ductile fracture. The same behavior for PP/GnP nanocomposites at different filler loading was observed by Ahmad, Young, and Kinloch (2015).
CONCLUSION

PP/GnP nanocomposite fibers were successfully obtained with graphene mass loadings of up to 1% (w/w) by melt spinning. SEM images showed that platelets are stacked in some area on the fiber surface. GnP increased the overall thermal stability of the PP, slowing its degradation by thermal depolymerization. Furthermore, the degree of crystallization declined as the GnP content increased, reducing the tenacity of the yarn but improving its elastic modulus from 91.9 to 95.9 cN/tex. The fibers produced in this study should be further characterized in relation to their electrical properties in order to investigate their promising applications in the production of smart textiles.

However, there are still several challenges that should be addressed for these nanocomposite fibers to reach their full potential. To maximize the benefits of graphene effectively in nanocomposites, they must not form aggregates and must be well dispersed in the polymer matrix. This could be achieved with the creation of covalent bonding or additional non-covalent binding interactions such as $\pi-\pi$ interactions or hydrogen bonding in order to improve interfacial adhesion in GnP/PP nanocomposite fibers.

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REFERÊNCIAS


