

## Research Article

# Effect of Expanded Graphite on Mechanical and Tribological Properties of Polyamide 6/Glass Fibre Composites

Dajana Japić,<sup>1</sup> Simon Kulovec <sup>1</sup>, Mitjan Kalin <sup>2</sup>, Janez Slapnik <sup>3</sup>, Blaž Nardin <sup>3</sup>, and Miroslav Huskić <sup>3</sup>

<sup>1</sup>Podkrižnik d.o.o., Ljubno ob Savinji, Slovenia

<sup>2</sup>University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia

<sup>3</sup>Faculty of Polymer Technology, Slovenj Gradec, Slovenia

Correspondence should be addressed to Miroslav Huskić; [miroslav.huskić@ftpo.eu](mailto:miroslav.huskić@ftpo.eu)

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The quality of plastic gears, especially their durability, is becoming increasingly important due to advances in electric mobility. Therefore, new materials are being developed that must have better mechanical properties, high thermal conductivity for heat dissipation, and tribological properties. The composites of expanded graphite (EG) and glass fibre-reinforced polyamide 6 (PA6/GF) were prepared, and the effect of EG particle size ( $\sim 5 \mu\text{m}$  (EG5) and  $\sim 1000 \mu\text{m}$  (EG1000)) on these properties was investigated. Composites with different contents (2–10 wt%) of EG in PA6/GF were prepared using a laboratory twin-screw extruder and then injection moulded in the form of rods and discs required for thermal, thermomechanical, and tribological tests. EG acted as a nucleating agent but hindered the crystallization rate at higher concentrations, which was more pronounced when EG5 was added. Dynamic mechanical analysis showed that the storage modulus increased with the addition of both types of EG. However, the addition of EG5 increased the storage modulus more than EG1000. The lowest coefficient of friction was obtained by the addition of 10 wt% EG5. The wear increased with the addition of both types of EG, only slightly with the addition of EG1000. The thermal conductivity of the composites with EG increased from 0.42 W/mK to 1 W/mK. The results show that the use of EG with smaller particle size is much more beneficial than with a larger one.

## 1. Introduction

Polymers are used in various applications where the durability of the product depends heavily on the mechanical as well as on the tribological properties of polymers. Therefore, for several years, there has been an increasing interest in studying the influence of various solid lubricants and other fillers, especially nanofillers, on these properties.

To improve mechanical properties such as tensile strength, hardness, impact strength, and dimensional stability, polymers are usually filled with glass fibres (GF), basalt fibres, carbon fibres, and more recently natural fibres [1–5]. To improve the thermal, electrical, and tribological properties of polymers, various graphite powders are widely used as fillers [6, 7]. To improve only tribological properties of polymers, other additives, such as MoS<sub>2</sub>, wax, polytetrafluoroethylene (PTFE), and

ultrahigh molecular weight polyethylene (UHMWPE), have also been used [8–11].

Various types of graphite, such as natural, synthetic, expanded (EG), or expandable graphite, are often added to polymers to improve thermal and electrical conductivity as well as mechanical and tribological properties. However, scientific results do not always confirm its positive influence on subsequent properties. Suresha et al. reported that graphite reduced the coefficient of friction (COF) and wear rate and improved the thermal conductivity and mechanical properties of epoxy composites [12]. The reduction of COF due to the addition of graphite was also observed in polyimide, especially at high load and high sliding velocity [8]. An increase in COF was observed in acrylic elastomer/EG when the composite was made from latex. In contrast, a decrease in COF was observed for the same composite prepared by

direct mixing [13]. The results show that the influence of the composite preparation method on tribological properties cannot be neglected. In thermoplastic polyurethane, the addition of graphite decreased the COF but increased the wear rate [14]. However, the tribological behaviour depends not only on the graphite content but also on the particle size and the mating material. The COF and wear of polystyrene (PS) against steel were much higher than those against PA66. Besides, the graphite particle size played an important role against steel, but not against PA66 [15].

Polyamides are engineering semicrystalline polymers with various useful properties. There are several types of polyamides (PA6, PA66, PA12, etc.) of which PA66 and PA6 are widely used in mechanical engineering. Due to the good mechanical and tribological properties, PA6 is one of the main polymers for the production of plastic gears, which are more and more used as substitutes for metal gears.

The influence of different types of graphite on the properties of PA6, which is the subject of our work, was also studied; however, various results were reported. You et al. reported that the addition of graphite (particle size  $25\ \mu\text{m}$ ) to PA6/GF increased COF and wear [16]. In contrast, Unal and Mimaroglu found a decrease in COF and wear for PA6/graphite composites. Better results were obtained for composites with 5% than for 15% of graphite [17]. Xu et al. obtained the lowest COF and wear with the addition of 1% graphite (particle size  $< 38\ \mu\text{m}$ ). Further increase (up to 10%) increased both parameters to approximately the same values as with pure PA6 [18]. In contrast, Sathees Kumar and Kanagaraj determined the optimum concentration of graphite (particle size  $250\ \mu\text{m}$ ) in PA6, which gave the lowest COF and wear rate, to be 20% [19].

The results on mechanical properties of PA6/graphite composites are similar to the results on tribological properties and therefore inconclusive. Uhl et al. prepared PA6/graphite composites by melt blending, using a variety of graphites, including virgin graphite and expandable and expanded graphite in concentrations up to 5%. Results for Young's modulus scattered with concentration and type of graphite and were mostly lower, especially after annealing at  $120^\circ\text{C}$ . The increase in modulus was observed for composites with EG. Dynamic mechanical analysis (DMA) also showed that the storage moduli ( $E'$ ) for PA6/graphite nanocomposites were mostly lower than those for neat PA6 [20]. Zhou et al. prepared PA6 composites with high loadings (up to 60 wt%) of low-temperature expandable graphite (LTEG) by an in situ exfoliation melting process. Their DMA analysis showed that the incorporation of LTEG significantly increased the storage modulus [21].

Unal et al. prepared composites of PA6 containing 5–15% of graphite. Tensile strength, elongation at break, impact strength, and specific wear rate decreased, while modulus of elasticity and hardness increased with increasing graphite content [22]. Uhl et al. also reported a decrease in tensile strength and elongation, while they observed no significant change in elastic modulus for different graphite types at concentrations up to 5% [20]. Sathees Kumar and Kanagaraj observed an increase in tensile and impact

strength as well as the Shore hardness with graphite addition up to 20%. However, modulus decreased at all graphite concentrations being highest at 20% [19]. Other authors report an increase in tensile and impact strength and a decrease in hardness [1].

In addition to the various types of graphite, other solid lubricants have also been used to improve the tribological properties of PA6. Li et al. reported the effects of PTFE, graphite, UHMWPE, and their mixtures on the mechanical and tribological properties of glass fibre-reinforced polyamide 6 (PA6/GF) [1]. The results showed that graphite could increase the tensile strength of the PA6/GF composite, but at the same time, the material became soft. The combination of PTFE/UHMWPE solid lubricants was the best choice to improve the friction and wear performance. PTFE, UHMWPE, and  $\text{MoS}_2$  were also tested to improve the tribological properties of the PA6/ $\text{TiO}_2$  composite. The lowest COF and wear rate were observed when PTFE was added, while  $\text{MoS}_2$  increased both values. A synergistic effect was observed when all three solid lubricants were combined [9].

The variability in observed results, both in terms of tribological and mechanical properties, may be a consequence of several factors, such as differences in the methods of composite preparation and differences in particle size and shape. Particle size and shape are very often not even mentioned in the literature. There are very few systematic studies on the influence of graphite particle size on the tribological performance of the material. However, contrary results can be found. A decrease in COF and wear rate with decreasing graphite particle size has been found for PEEK and PAEK composites [23, 24], while the opposite has been observed for polybenzoxazine composites [25].

Therefore, the main objective of this work was to investigate the influence of expanded graphite concentration (2–10 wt%) and particle size ( $5\ \mu\text{m}$  and  $1000\ \mu\text{m}$ ) on the thermal, mechanical, and tribological properties of polyamide 6/glass fibre composites. Relatively low content of EG was added to maintain the toughness of composites.

## 2. Materials and Methods

**2.1. Materials.** Polyamide 6 (Durethan BKV 30 H3.0) reinforced with 30% glass fibre was used as a matrix. Expanded graphite powder Thermophit™ GFG5 and GFG1000 HD with a median grain size ( $D_{50}$ ) of  $\sim 5\ \mu\text{m}$  (EG5) and  $\sim 1000\ \mu\text{m}$  (EG1000), respectively, were kindly donated by SGL Group GmbH, Meitingen, Germany.

**2.2. Preparation of Composite Materials.** Composites of PA6/GF, with two types of expanded graphite, were prepared using a Dr. Collin ZK 25T twin-screw extruder at  $250^\circ\text{C}$  and 60 rpm. The concentrations of EG5 in the composites were 2, 4, 6, 8, and 10 wt%. Due to the large particle size of EG1000, we were unable to maintain a constant feed at low loadings, so only composites containing 6, 8, and 10 wt% EG1000 were prepared. The samples were designated as shown in Table 1.

A Babyplast injection moulding machine was used to prepare test specimens required for the thermal, mechanical,

TABLE 1: Storage modulus determined at 25°C and thermal conductivity of glass fibre-reinforced PA6 composites with the addition of expanded graphite EG5 and EG1000.

| Composites           | Sample | Storage modulus $E'$ (MPa) | Thermal conductivity (W/mK) |
|----------------------|--------|----------------------------|-----------------------------|
| PA6/GF               | A      | 5391 ± 232                 | 0.42                        |
| PA6/GF/<br>2%EG5     | B2     | 5540 ± 222                 | 0.54                        |
| PA6/GF/<br>4%EG5     | B4     | 6021 ± 183                 | 0.66                        |
| PA6/GF/<br>6%EG5     | B6     | 6064 ± 150                 | 0.76                        |
| PA6/GF/<br>8%EG5     | B8     | 6201 ± 242                 | 0.88                        |
| PA6/<br>GF10%EG5     | B10    | 6560 ± 232                 | 1.01                        |
| PA6/GF/<br>6%EG1000  | C6     | 6118 ± 158                 | 0.81                        |
| PA6/GF/<br>8%EG1000  | C8     | 5639 ± 158                 | 0.96                        |
| PA6/GF/<br>10%EG1000 | C10    | 5651 ± 189                 | 1.04                        |

and tribological tests. The temperature of the nozzle was 275-290°C, and the temperature of the mould was 90°C.

**2.3. Instruments and Measurements.** The dispersion of graphite in the PA6/GF matrix was studied by scanning electron microscopy (SEM) using a Zeiss Supra 35 VP microscope at an accelerating voltage of 1 kV. The samples were cooled in liquid nitrogen and fractured before measurement.

Viscoelastic properties were measured with a TA Q800 dynamic mechanical analyzer (DMA) using a dual cantilever. Rectangular specimens (55 × 10 × 1.5 mm) were heated from 0°C to 200°C at a heating rate of 3°C/min, an amplitude of 15 μm, and a frequency of 1 Hz.

Differential scanning calorimetry (DSC) was performed using a Mettler Toledo DSC1 calorimeter. Samples were heated/cooled/heated, at heating and cooling rates of 10°C/min each.

Tribological tests were performed with a unidirectional sliding motion in a UMT-2 tribometer (Bruker, Campbell, CA, USA) at a room temperature around 25°C. Before testing, the specimens were polished in a sequence of different grinding and polishing steps to achieve the final roughness of Ra = 0.30 μm. The tests were performed at a rotation frequency of 7.234 Hz and a normal load of 6 N.

Thermal conductivity was measured using the Thermal Constants Analyser TPS 1500. The measurement time was 20 s, and the heating power was 20 mW.

X-ray diffraction patterns were determined using a PANalytical X'Pert PRO X-ray diffractometer ( $\lambda = 1.54 \text{ \AA}$ ,  $2\theta = 2 - 60^\circ$ , step 0.33°).

### 3. Results and Discussion

Graphites EG5 and EG1000 differ not only in particle size but also in particle structure (Figure 1). EG5 is in the form of small flat particles whose thickness is mostly in the nanometer range. At higher magnification, it is easy to see that the particles are composed of many flat particles of different shapes and sizes bound to each other. The particles of EG1000 are larger and more compact. Even at higher magnifications, there were hardly any sharp edges in nanometer size to be found.

The difference in structure is also evident in the XRD diffractograms, which show only three diffractions (Figure 2). The diffractograms differ greatly in signal intensities and slightly in the position of the peaks, which are located at 26.5°, 44.3°, and 54.5°, corresponding to planes (002), (101), and (004), respectively [25]. A sharp diffraction peak centred at  $2\theta = 26.5^\circ$  represents well-ordered graphene stacks with an interlayer spacing of 3.35 Å. The Scherrer equation was used to calculate the crystallite sizes of the graphites, which are 25.7 nm and 20.3 nm for EG1000 and EG5, respectively.

Figure 3 shows the dependence of storage modulus as a function of temperature for the composites with an addition of 10 wt% filler. The storage moduli ( $E'$ ) were increased by the addition of both types of EG, which is in agreement with some previous findings [20, 21]. Increasing the EG5 concentration up to 10 wt% increases the storage modulus, while a sharp increase, followed by a decrease in modulus, is observed for EG1000. A decrease is a consequence of aggregation of large G1000 particles at higher concentrations and formation of voids in the material. The results are shown in Table 1.

The composites with EG exhibited higher storage modulus only below the glass transition, above which it was the same or even slightly lower. This may be attributed to low interactions between EG and the softened polymer, which slips under the load on the surface of the higher modulus EG. The reinforcing effect of the filler at higher temperatures is therefore not observed.

The glass transition temperature, determined from the peak of the loss modulus, did not change with the addition of EG and was  $44 \pm 2^\circ\text{C}$  (Figure 3). For clarity, only the measurements for pure PA6 and the composites with 10 wt% of graphite are shown.

Thermal conductivity is an important parameter for various industrial applications such as electronics, heat exchangers, and plastic gears. Carbon-based materials, especially carbon nanotubes and graphene, are known for their excellent thermal conductivity. Graphite and carbon black do not perform as well but are cheaper and therefore more suitable for most applications. The thermal conductivity of composites depends on the size and aspect ratio of the fillers, the interactions between the filler and the polymer, the dispersion of the fillers, the crystallinity of the polymer matrix, and even the orientation of polymer molecules [26].

The thermal conductivity of the prepared composites increased by increasing the amount of expanded graphite of both sizes. The addition of 10 wt% graphite increased

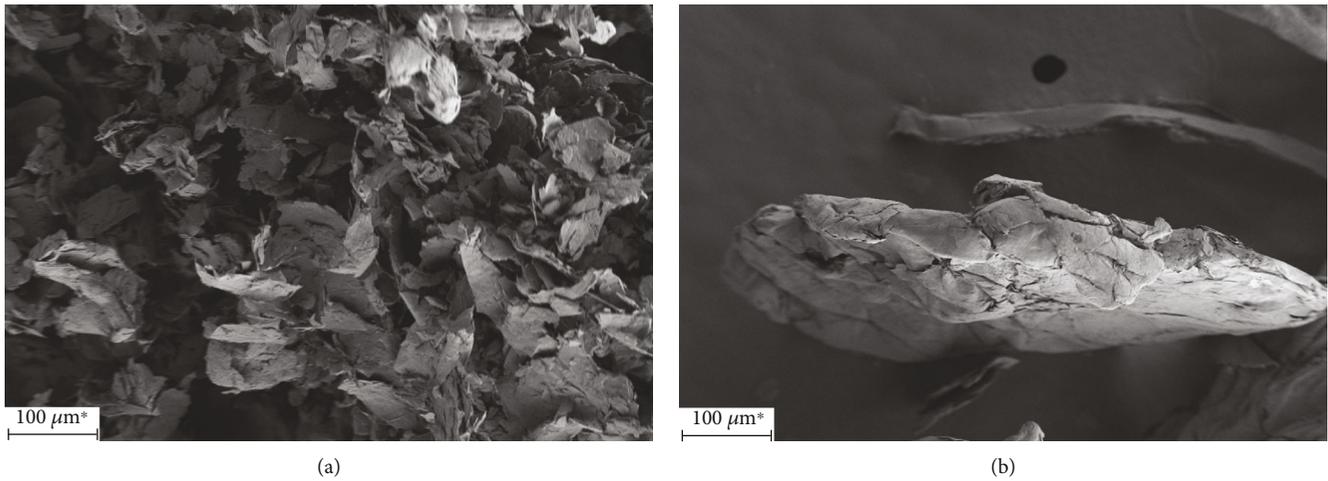


FIGURE 1: SEM micrograph of EG5 ((a) magnification 5,000x) and EG1000 ((b) magnification 5,000x).

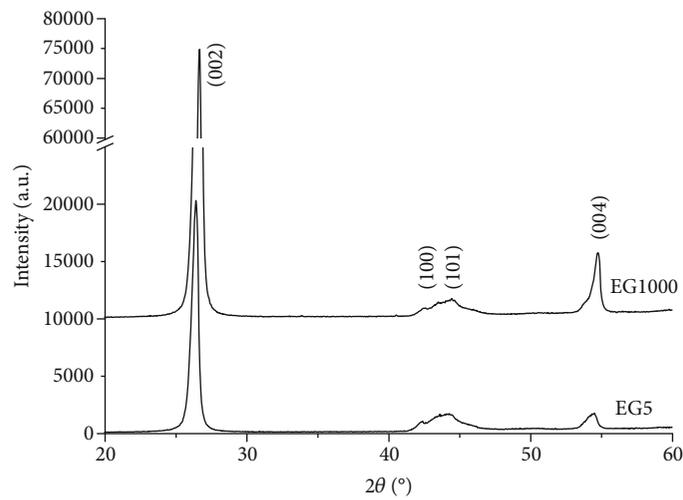


FIGURE 2: XRD spectra of graphites EG5 and EG1000.

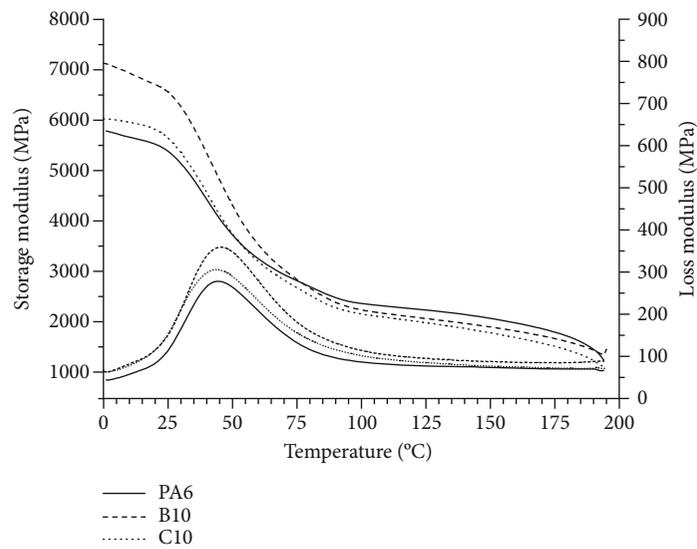


FIGURE 3: The dependence of storage and loss modulus on temperature for PA6-GF and composites with 10 wt% EG.

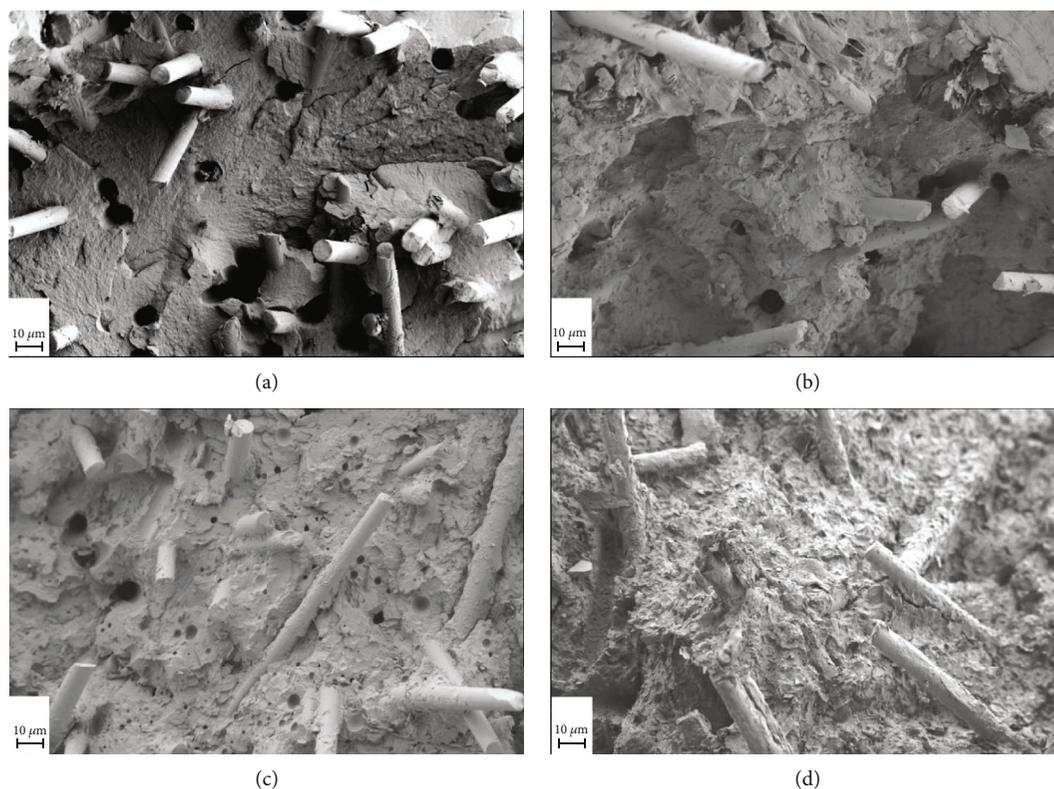


FIGURE 4: SEM micrograph of PA6/GF (a) and composite with 10 wt% EG1000 (b), 2% EG5 (c), and 10% EG5 (d). Magnification 1000x.

the thermal conductivity by 150%. Slightly higher values were obtained for EG1000 composites. Almost equal thermal conductivity is surprising since large particles with good thermal conductivity can transport heat from one side to the other very fast. On the other hand, much smaller particles are better distributed within the polymer, which leads to a higher surface area and better heat transfer. The results are shown in Table 1.

The fracture surfaces of the PA6/GF composite prepared by the addition of different amounts of EG were characterized by SEM. The surface of the polyamide matrix in PA6/GF (Figure 4(a)) is relatively smooth, as is the surface of the glass fibres. The fibres are pulled out of the PA6, indicating weak interactions between the polymer and the glass fibres. Similar observations were made for composites with EG1000. However, in Figure 4(b), large graphite particles can be seen. Due to the strong shear forces during extrusion, the EG1000 particles were broken up and their structure was no longer as compact as shown in Figure 1. Therefore, thin graphite sheets were easily visible at higher magnifications. The surface of the glass fibres was still mostly smooth, but small polymer particles adhering to the fibres could be seen in some places. A different structure was observed for the composites containing 2 wt% and 10 wt% EG5 (Figures 4(c) and 4(d), respectively). The surface of the polyamide was rough. Graphite particles could not be observed as a separate phase at any magnification. The surface of the glass fibres was also rough and covered with the polymer matrix. Although the fibres were pulled out, the holes with

the sharp edges were practically not observed in sample B10. It appears that the small EG particles acted as a compatibilizer and enhanced the interactions between the glass fibres and the PA6 matrix, which also resulted in increased stiffness as determined by DMA measurements.

It is well known that the addition of fillers to a semicrystalline polymer can affect both the crystallization kinetics and the degree of crystallinity. Different results were obtained for different polymers. EG acted as a nucleating agent in high-density polyethylene. The crystallization peak shifted by 3°C toward higher temperature, the melting temperature decreased by 2°C, and the overall crystallinity decreased from 86% to 66% with increasing EG content up to 10 wt% [27]. Similar results, but with increasing degree of crystallinity, were also obtained for poly(phenylene sulfide) [28]. For PA6 composites, in situ expanded graphite increased the peak crystallization temperature from 170°C up to 195°C and increased the degree of crystallinity at lower loadings (5-10%), while a further increase to 35% decreased the crystallinity [21].

Similar results have been obtained in our experiments. Although the peak crystallization temperature was shifted only 1-2°C to a higher temperature, the crystallization of composites started ( $T_{cs}$ ) at 10-15°C higher temperature. Thus, the crystallization temperature range was much broader. The melting enthalpy slightly increased with the addition of up to 6 wt% graphite and decreased above this level. Both crystallization and melting are more affected by EG5 than by EG1000. This can be explained by the better

TABLE 2: Peak melting and crystallization temperature ( $T_m$ ,  $T_c$ ), melting and crystallization enthalpy ( $\Delta H_m$ ,  $\Delta H_c$ ), and the starting temperature of crystallization ( $T_{cs}$ ).

| Sample | $T_m$ (°C) | $\Delta H_m^*$ (J/g) | $T_c$ (°C) | $\Delta H_c^*$ (J/g) | $T_{cs}$ (°C) |
|--------|------------|----------------------|------------|----------------------|---------------|
| A      | 219.4      | 49.1                 | 190.6      | 44.0                 | 202           |
| B2     | 219.9      | 50.7                 | 192.4      | 44.5                 | 215           |
| B4     | 219.9      | 50.9                 | 192.0      | 44.6                 | 215           |
| B6     | 219.9      | 52.2                 | 192.2      | 45.5                 | 215           |
| B8     | 219.5      | 46.6                 | 190.9      | 39.9                 | 215           |
| B10    | 219.4      | 47.1                 | 190.1      | 39.6                 | 215           |
| C6     | 220.2      | 51.2                 | 191.4      | 46.0                 | 211           |
| C8     | 220.2      | 50.9                 | 191.5      | 45.5                 | 213           |
| C10    | 219.9      | 50.8                 | 191.7      | 45.2                 | 215           |

\*Recalculated on the content of PA6/GF.

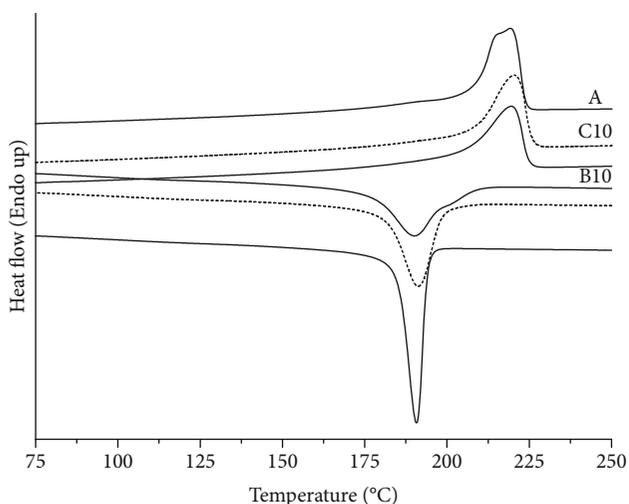


FIGURE 5: The cooling and the second heating DSC curves of composites: PA6/GF (A), PA6/GF/10%EG5(B10), and PA6/GF/10%EG1000 (C10).

dispersion of smaller particles, which acted as a better nucleating agent on the one hand, but on the other hand, the high number of finely dispersed flakes hindered the crystallization process due to the limited space between the flakes. Large and thick particles of EG1000 are less dispersed; therefore, the influence on crystallization and melting is much lower. The thermal characterization results are shown in Table 2 and Figure 5. For clarity, only DSC thermograms of the composites with 10 wt% of EG are shown.

The coefficient of friction of PA6 was 0.292 and was not significantly changed by the addition of EG5 or EG1000. The addition of EG5 slightly reduced the CoF at all concentrations, and the lowest value (0.27) was obtained for composites with 10 wt% EG5. This might be attributed to good dispersion of small particles within the polymer matrix, which acted as lubricants. The highest coefficient of friction (0.301) was obtained for composites with 10 wt% EG1000. The results of the influence of particle size on CoF are in agreement with the findings for PAEK-graphite composites

TABLE 3: Coefficient of friction (CoF) and wear of PA6/GF and composites with EG5 and EG1000.

|     | CoF ( <i>f</i> )  | Wear ( $\times 10$ [7] mm <sup>3</sup> /nm) |
|-----|-------------------|---|
| A   | 0.292 $\pm$ 0.011 | 5.49 $\pm$ 0.30                             |
| B2  | 0.277 $\pm$ 0.013 | 6.66 $\pm$ 1.00                             |
| B6  | 0.285 $\pm$ 0.030 | 9.35 $\pm$ 1.40                             |
| B10 | 0.270 $\pm$ 0.036 | 18.77 $\pm$ 3.40                            |
| C6  | 0.283 $\pm$ 0.007 | 6.27 $\pm$ 0.60                             |
| C10 | 0.301 $\pm$ 0.010 | 6.96 $\pm$ 0.80                             |

[23]. Nevertheless, the differences are quite small, only up to 8%. The detailed data are presented in Table 3.

Wear increased with the addition of both EG but only slightly when EG1000 was added. The results are in agreement with previous findings for polyurethane composites [14] but not for PAEK [23]. Increased wear is a result of a softer surface or poor interfacial adhesion between the filler and matrix.

#### 4. Conclusions

The influence of the amount of expanded graphite and particle size (5  $\mu$ m and 1000  $\mu$ m) on the mechanical, thermal, and tribological properties of glass fibre-reinforced PA6 composites was investigated. Thermomechanical analysis showed that the storage modulus increased with the addition of both types of EG. Increasing the concentration of EG5 up to 10 wt% increased the storage modulus by 22%. However, the highest increase in modulus (13%) of EG1000/PA6 was observed at 6 wt% EG1000. Above this concentration, the modulus decreased to almost the same value as for pristine glass fibre-reinforced PA6. EG had no effect on the glass transition temperature of PA6.

The addition of EG, especially EG5, acted as a nucleating agent for the crystallization of PA6, and crystallization started at 10-13°C higher temperature. However, the confined space between the dispersed graphite flakes hindered the crystal formation, especially at EG5 concentrations higher than 6 wt%. The degree of crystallinity decreased with increasing EG5 concentration from 6 wt% to 10 wt%. Nucleation, although much weaker, was also observed with EG1000 but not the negative effect on the degree of crystallinity. This was explained by the presence of much larger and thicker EG particles, which are not finely dispersed in PA6 and therefore cannot hinder crystallization.

The particle size of EG affected the tribological properties. The lowest coefficient of friction was obtained by adding 10 wt% EG5. However, wear was highest for this composite. Wear also increased, but only slightly, when EG1000 was added.

All PA6/GF with expanded graphite had higher thermal conductivity, and no large difference was found between EG5 and EG1000.

## Data Availability

The data that support the findings of this study are openly available at <https://www.dropbox.com/sh/nn3u8bvjzow6xen/AADjSCEvdwa2Db3FZmE7D4FEa?dl=0>.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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## References

- [1] D. Li, Y. Xie, W. Li, Y. You, and X. Deng, "Tribological and mechanical behaviors of polyamide 6/glass fiber composite filled with various solid lubricants," *Scientific World Journal*, vol. 2013, p. 320837, 2013.
- [2] R. Loendersloot, S. V. Lomov, R. Akkerman, and I. Verpoest, "Carbon composites based on multiaxial multiply stitched preforms. Part V: Geometry of sheared biaxial fabrics," *Composites. Part A, Applied Science and Manufacturing*, vol. 37, no. 1, pp. 103–113, 2006.
- [3] V. Chaudhary and F. Ahmad, "A review on plant fiber reinforced thermoset polymers for structural and frictional composites," *Polymer Testing*, vol. 91, article 106792, 2020.
- [4] C. R. Raajeshkrishna, A. S. Pradeep, and R. D. Rishi Kumar, "Influence of fiber content on mechanical, tribological properties of short basalt fiber-reinforced nylon 6 and polypropylene composites," *Journal of Thermoplastic Composite Materials*, vol. 34, p. 765, 2021.
- [5] P. Sahu and M. K. Gupta, "A review on the properties of natural fibres and its bio-composites: Effect of alkali treatment," *Proceedings of the Institution of Mechanical Engineers, Part L: The Journal of Materials: Design and Applications*, vol. 234, no. 6, pp. 198–779, 2020.
- [6] X. Wu, J. Qiu, P. Liu, and E. Sakai, "Preparation and characterization of polyamide composites with modified graphite powders," *Journal of Polymer Research*, vol. 20, no. 11, p. 20, 2013.
- [7] P. Zhang, B. Wang, and J. Bin, "Two-component acrylic structural adhesive initiated by tributylborane for untreated PET adhesion," *Applied Polymer Science*, vol. 135, no. 32, p. 135, 2018.
- [8] P. Samyn and G. J. Schoukens, "On the efficiency of internal lubricants for polymers under different sliding conditions," *Journal of Vinyl & Additive Technology*, vol. 14, no. 3, pp. 126–135, 2008.
- [9] Y. L. You, D. X. Li, G. J. Si, and X. Deng, "Investigation of the influence of solid lubricants on the tribological properties of polyamide 6 nanocomposite," *Wear*, vol. 311, no. 1-2, pp. 57–64, 2014.
- [10] J. Horský, J. Kolařík, and L. Fambri, "Structure and mechanical properties of composites of poly(6-hexanelactam) combining solid tribological additives and reinforcing components," *Macromolecular Materials and Engineering*, vol. 289, no. 4, pp. 324–333, 2004.
- [11] M. Doumeng, F. Berthet, K. Delbé, O. Marsan, J. Denape, and F. Chabert, "Effect of size, concentration, and nature of fillers on crystallinity, thermal, and mechanical properties of polyetheretherketone composites," *Journal of Applied Polymer Science*, vol. 139, no. 5, p. 51574, 2022.
- [12] B. Suresha, Siddaramaiah, Kishore, S. Seetharamu, and P. S. Kumaran, "Investigations on the influence of graphite filler on dry sliding wear and abrasive wear behaviour of carbon fabric reinforced epoxy composites," *Wear*, vol. 267, no. 9-10, pp. 1405–1414, 2009.
- [13] Y. Quan, M. Lu, M. Tian, S. Yan, Z. Yu, and L. Zhang, "Functional and mechanical properties of acrylate elastomer/expanded graphite nanocomposites," *Journal of Applied Polymer Science*, vol. 130, no. 1, pp. 680–686, 2013.
- [14] B. Golaz, S. Tetouani, N. Diomidis, V. Michaud, and S. Mischler, "Processing and tribology of thermoplastic polyurethane particulate composite materials," *Journal of Applied Polymer Science*, vol. 125, no. 5, pp. 3745–3754, 2012.
- [15] R. Gilardi, "Tribology of Graphite-Filled Polystyrene," *Lubricants*, vol. 4, no. 2, p. 20, 2016.
- [16] Y. L. You, D. X. Li, X. Deng, W. J. Li, and Y. Xie, "Effect of solid lubricants on tribological behavior of glass fiber reinforced polyamide 6," *Polymer Composites*, vol. 34, no. 11, pp. 1783–1793, 2013.
- [17] H. Unal and A. Mimaroglu, "Friction and wear performance of polyamide 6 and graphite and wax polyamide 6 composites under dry sliding conditions," *Wear*, vol. 289, pp. 132–137, 2012.
- [18] H. Xu, Z. Feng, J. Chen, and H. Zhou, "Tribological behavior of the polyamide composite coating filled with different fillers under dry sliding," *Journal of Applied Polymer Science*, vol. 104, no. 4, pp. 2554–2560, 2007.
- [19] S. Sathees Kumar and G. Kanagaraj, "Investigation on Mechanical and Tribological Behaviors of PA6 and Graphite-Reinforced PA6 Polymer Composites," *Arabian Journal for Science and Engineering*, vol. 41, pp. 4347–4357, 2016.
- [20] F. M. Uhl, Q. Yao, H. Nakajima, E. Manias, and C. A. Wilkie, "Expandable graphite/polyamide-6 nanocomposites," *Polymer Degradation and Stability*, vol. 89, no. 1, pp. 70–84, 2005.
- [21] S. Zhou, L. Yu, X. Song, J. Chang, H. Zou, and M. Liang, "Preparation of highly thermally conducting polyamide 6/graphite composites via low-temperature in situ expansion," *Journal of Applied Polymer Science*, vol. 131, no. 1, p. 131, 2014.
- [22] H. Unal, K. Esmer, and A. Mimaroglu, "Mechanical, electrical and tribological properties of graphite filled polyamide-6 composite materials," *Journal of Polymer Engineering*, vol. 33, no. 4, pp. 351–355, 2013.
- [23] J. N. Panda, J. Bijwe, and R. K. Pandey, "Variation in size of graphite particles and its cascading effect on the performance properties of PAEK composites," *Composites. Part B, Engineering*, vol. 182, p. 107641, 2020.
- [24] Y. Shang, Y. Zhao, Y. Liu, Y. Zhu, Z. Jiang, and H. Zhang, "The effect of micron-graphite particle size on the mechanical and tribological properties of PEEK Composites," *High Performance Polymers*, vol. 30, p. 153, 2017.
- [25] S. Peng, X. Fan, S. Li, and J. Zhang, "Green synthesis and characterization of graphite oxide by orthogonal experiment,"

- Journal of the Chilean Chemical Society*, vol. 58, no. 4, pp. 2213–2217, 2013.
- [26] M. Ajourloo, M. Fasihi, M. Ohshima, and K. Taki, “How are the thermal properties of polypropylene/graphene nanoplatelet composites affected by polymer chain configuration and size of nanofiller?,” *Materials and Design*, vol. 181, p. 108068, 2019.
- [27] W. Zheng, X. Lu, and S. C. Wong, “Electrical and mechanical properties of expanded graphite-reinforced high-density polyethylene,” *Journal of Applied Polymer Science*, vol. 91, no. 5, pp. 2781–2788, 2004.
- [28] Y. F. Zhao, M. Xiao, S. J. Wang, X. C. Ge, and Y. Z. Meng, “Preparation and properties of electrically conductive PPS/expanded graphite nanocomposites,” *Composites Science and Technology*, vol. 67, no. 11-12, pp. 2528–2534, 2007.