Rheological, thermal, and electrical characterization polyamide/polypropylene blend composites containing hybrid filler: Boron nitride and reduced graphene oxide

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Abstract
In this study, the microstructural development and its effect on the thermal conductivity of polyamide6 (PA6)/polypropylene (PP) blends containing boron nitride (BN) and reduced graphene oxide (rGo) as hybrid fillers were investigated. Blend samples were prepared using the masterbatch method to localize BN and rGo in the matrix phase (PA6). Dynamic rheological results were consistent with selective localization of the fillers in PA6 as evidenced by non-terminal behavior (3D network) PP/PA-BN at low frequencies. Compared with the case where the matrix phase (PA6) was only filled with BN particles, thermal conductivity measurements showed that replacing 10% and 15% BN particles with rGo nanoparticles yielded higher thermal conductivity. The hybrid fillers had a synergetic effect on the heat conductive network, forming a more efficient percolating network of BN and rGo in the matrix phase (PA6). A comparison between the BN-filled PA6 blend and the BN-rGo-filled PA6 blend revealed higher thermal conductivity in the PP/PA6-BN-rGo sample with co-continuous morphology than in the PP/PA6-BN sample with matrix-disperse morphology.

KEYWORDS
electrical insulating composite, hybrid composites, interface, phonon scattering, rheology, synergism, thermal conductivity, thermally conductive composite

1 INTRODUCTION
The technological advancement in the different industrial sections has led to an exponential increase in power densities, which in turn drove the innovation of smarter and smaller products. The electronics industry has undergone rapid growth from low-performing toward advanced devices with high computational powers and speeds, regarding thermal management innovations based on miniaturization technologies. Heat is an inevitably disadvantageous by-product of any electronic device, reducing their reliabilities and performance. Thus, heat dissipation management has become a significant challenge. In many applications, Electronic components are attached to substrates and base plates that are capable of dissipating the heat generated by devices. In many cases,
electronic components often fail because of damage resulting from excessive operating temperatures or other thermal factors such as mechanical stresses due to temperature differences.

A great deal of researcher tendency has recently been directed toward using thermally conductive polymer composites to dissipate heat in electronic devices. Polymer materials are extensively utilized as substrate materials, printed circuit boards, semiconductors, and insulators for numerous electronic packaging applications due to their low density, low cost, and ease of production. Nevertheless, they have the main drawback of low thermal conductivity. Thermally conductive polymer composites have been prepared traditionally by incorporating conductive fillers, including carbon-based fillers, metal-based fillers, and ceramic-based fillers, into the polymeric matrix. For most cases, a high amount of filler, usually higher than 60 wt%, must be introduced into a matrix in order to achieve percolation thresholds and form continuous conductive pathways in the polymer matrix. However, a high filler loading could result in insufficient mechanical properties, high density, and complex processing.

It is well known that the polymer composite’s performance has been significantly ameliorated via incorporating nano-fillers into polymers. The carbon nanomaterials have been a highly efficient filler due to their high aspect ratio and superior electrical properties, which help reduce the filler volume fraction and maintains relatively high thermal and electrical conductivity in the polymer composite. Besides, reducing the filler content solves the issues associated with high density and poor mechanical properties. Among carbon-based fillers, carbon nano-tubes (CNTs) and graphene have been drawn much attention due to their high electrical and thermal conductivity and large aspect ratio. Their thermal conductivity has been theoretically shown to be nearly 2000–6000 and 5000 W m\(^{-1}\) K\(^{-1}\), respectively. However, the addition of carbon-based fillers into polymers results in composites that are not only thermal conductive but also electrically conductive, which is not favorable. Hence, carbon materials cannot meet the requirement of electronic devices for both electrical insulation and high thermal conductivity.

In recent years, ceramic-based fillers have widely been used to fabricate high thermally conductive polymer composites. Ceramic-based fillers, such as boron nitride (BN), aluminum nitride (AlN), silicon carbide (SiC), and aluminum oxide (Al\(_2\)O\(_3\)), have drawn more attention as thermally conductive fillers due to their high thermal conductivity and high electrical resistivity. In ceramic materials, because of the lack of free electrons, phonons are responsible for thermal conduction. Among ceramic-based fillers, BN proved to be the right choice due to its relatively high thermal conductivity.

BN typical 2D structure is much like that of graphene, showing a platelet-like structure while exhibiting a much lower thermal conductivity of approximately 250–300 W m\(^{-1}\) K\(^{-1}\). In comparison to graphene, BN shows very low electrical conductivity. Having both high thermal conductivity and low electrical conductivity makes BN-filled composite a perfectly suitable candidate for special applications in the electronic packaging industry.

Based on the explanation mentioned above, two main issues are in the way of improving thermal conductivity by conductive fillers. First, electrical insulation is often lost after adding the carbon-based fillers because free electrons are responsible for heat conduction. Second, although ceramic-based fillers have high thermal conductivity and electrical resistivity, it seems that the high content of fillers must be used to achieve appropriate thermal conductivity.

As an aspiration to see the high thermal conductivity of carbon-based fillers, it is interesting to find out what happens if carbon-based and ceramic-based fillers are introduced into the composites simultaneously. Recently, hybrid systems have been employed by incorporating multi-conductive fillers to enhance the thermal conductivity and reduce the filler content of the composite through the synergistic effect of the hybrid fillers. Yan-jun Xiao et al used BN and CNT fillers to achieve the mentioned synergistic effects on polyvinylidene fluoride (PVDF) composites. Their results were indicative of a greatly augmented thermal conductivity for the PVDF/BN/CNT compared to PVDF/BN composite. Choi et al also found the same effects on epoxy composites when combining MWCNTs and AlN.

Wang et al fabricated a thermally conductive nanocomposites based on PVDF by using hexagonal boron nitride (hBN) nanosheets and functionalized silicon carbide (f-SiC) nanowires. The hBN nanosheets make bridges between the oriented f-SiC nanowires and enhanced thermal conductivity of the PVDF-based composite by forming the hBN and f-SiC hybrid filler networks. In another study, Jiang et al investigated the synergistic effect of graphene and alumina on improving thermal conductivity of polylactic acid composites. The results demonstrated that a higher thermal conductivity is achieved when both fillers introduced to the composites in comparison with composites filled with only graphene or alumina. It indicates that the synergistic effect and construction of effectively thermal conduction network structure in the composites play a decisive role in thermal conduction. Bridging of graphene and alumina forms a 3D network structure through the composite which greatly improve the thermal conductivity.
BN and AlN, and significantly enhance the thermal conductivity value of the epoxy to 2.4 W m$^{-1}$ K$^{-1}$. Due to the perfect dispersion of BN and AlN, more phonon pathways created in the composites which substantially enhanced the thermal conductivity of epoxy composite (eight times more than the neat epoxy and two times more than single BN or AlN filling composite). Wang et al studied the effect of using hybrid fillers on the polybenzoxazine composites' thermal conductivity. Wang et al introduced BN and CNT as hybrid fillers in the polybenzoxazine matrix. CNT served as a bridge among BN platelets, and a continuous 3D thermally conductive network was formed in the composite, which led to a significant improvement of the thermal conductivity. Clearly, in the hybrid systems, the thermal conductivity can be significantly enhanced by incorporating fillers with a different base and tuning the fillers' microstructure.

In this study, microstructure development and thermal conductivity of polypropylene (PP)/polyamide (PA) blends containing BN and rGo as hybrid fillers were investigated. Emphasis was placed on exploring and understanding the possible synergistic effects of phonon–electron transfer as two distinct thermal conductivity routes induced by the hybrid fillers. The combination of BN platelets and reduced graphene oxide (rGo) Nanoplatelets were used as hybrid fillers to enhance the thermal conductivity of PP/PA6 immiscible blend. As a rule of thumb, a strategy of replacing a portion of the BN particles with rGos in the PA phase was employed to study the synergistic effect of phonon and electron interactions, as well as the resultant improvements in thermal conductivity. The idea is that rGos with a high aspect ratio might improve the thermal conductivity of the blended composites by forming bridges between the BN platelets. In contrast, the BN platelets may act as electrical current barriers to prevent the formation of the electrically conductive network within the composite. The primary objective of this study is to provide materials with both high electrical insulation and high thermal conductivity. An attempt was also made to illustrate how the hybrid fillers' localization affected the thermal conductivity of the blend nanocomposite and how the phonon-morphology relationship impacted the overall thermal conductivity of the composite.

## EXPERIMENTAL

### 2.1 Materials

PP (HP550j) with a density of 0.9 g cm$^{-3}$ and a melt flow index of 3.2 g/10min (210) were supplied from Jam Petrochemical Company (Iran). PA6 (Akulon F136) pellets with a density of 1.13 g cm$^{-3}$ were received from DSM, Netherlands. BN powder with a density of 0.3 g cm$^{-3}$ and an average diameter of 7 μm and an average thermal conductivity of 120 W m$^{-1}$ K$^{-1}$, with platelet shape with the surface area of 7 m$^{2}$/g, were purchased from Saint-Gobain, Co., USA. rGo (0.8–2 nm in diameter, 1–10 nm in length) was purchased from American Elements Co.

### 2.2 Sample preparation

Polymer blends and polymer composites with different compositions (Table 1) were prepared by melt compounding using a 60 cm$^3$ internal mixer (Brabender Plasticorder W50) at 240°C and 60 rpm. All masterbatches and PA6 blends were dried in an oven at 80°C for 24 h to remove moisture before use.

Two different feeding routes were employed to study the effects of the conductive filler localization on the blend morphology and thermal conductivity of the composite. In the first route, the conductive fillers (BN and the BN/rGo hybrid) were melt compounded with PA6 to produce PA blend masterbatches (PA-BN and PA-BN-rGo). Then, appropriate amounts of PA-BN and PA-BN-rGo were melt-mixed with PP to prepare PP/PA-BN, PP/PA-BN-rGo 10, and PP/PA-BN-rGo 15 nanocomposites. For all blend nanocomposites, the volume ratio of

| Sample          | BN mass ratio in PA6/filler | BN mass ratio in composite | rGo mass ratio in PA6/filler | rGo mass ratio in composite | rGo mass ratio in PP/rGo masterbatch |
|-----------------|-----------------------------|---------------------------|-----------------------------|-----------------------------|--------------------------------------|
| PA/BN           | 40%                         | 40%                       | —                          | —                          | —                                    |
| PP/PA-BN        | 40%                         | 32%                       | —                          | —                          | —                                    |
| PP/PA-BN-rGo 10 | 35%                         | 28%                       | 3.90%                      | 3.10%                      | —                                    |
| PP/PA-BN-rGo 15 | 34%                         | 27%                       | 5.90%                      | 4.70%                      | —                                    |
| PP-rGo/PA-BN    | 40%                         | 31%                       | —                          | 2.20%                      | 7.50%                                |

Abbreviations: BN, boron nitride; PA, polyamide; PP, polypropylene; rGo, reduced graphene oxide.
PP/(PA6-hybrid fillers) was kept constant at 30%/70%, and the volume ratio of PA6/(hybrid fillers) was kept constant at 60%/40%.

The second nanocomposite (PP-rGo/PA-BN) was prepared using the second preparation route, in which the rGo was first melt-compounded with PP to produce a PP-based masterbatch (PP-rGo). Then, the appropriate amount of PP-rGo was melt blended with a PA6/BN masterbatch. The volume ratios of PP/rGo and PA6/BN were set at 92.5%/7.5% and 60%/40%, respectively. The volume ratio of PP-rGo/PA6-BN was set at 30%/70%.

2.3 | Thermal conductivity measurements

Thermal conductivity measurements were taken by a hot plate device designed in the Polymer Engineering Department of Tarbiat Modares University. The samples were placed between two plates: one hot and one cold. The hot plate was heated and maintained at a higher temperature \( T_h \), while the cold plate was maintained at a lower temperature \( T_c \). The temperatures of both plates were monitored up to the point that they are constant. Thermal conductivity was then calculated based on the steady-state temperature, the heat input to the hot plate, and the samples’ thicknesses. All samples were compressed and shaped into disks (40 mm diameter, 4 mm thick).

2.4 | Morphology characterization

The morphology observation was made on the cryogenically fracture surfaces of the samples utilizing a field-emission scanning electron microscopy (FESEM, MIRA3TESCAN-XMU). The samples were cryogenically fractured in liquid nitrogen, and all of the fractured surfaces were coated with gold before FESEM observation to avoid charging by the electron beam.

2.5 | Dynamic rheological test

The oscillatory shear rheological measurements were carried out with MCR 301 rheometer (Physica Anton Paar, Austria) using parallel plate geometry with a diameter of 25 mm and a gap of 1 mm. All rheological measurements were performed in a nitrogen atmosphere to minimize the degradation of the samples. The oscillatory shear rheological measurements were conducted on the nanocomposites at a temperature of 240°C. The linear viscoelastic properties of nanocomposites were measured within the frequencies range of 0.1–1000 (1/s) with a small strain amplitude of 0.02% to the nanocomposites remain in their linear elastic deformation regime.

2.6 | Four-point test

The electrical conductivity measurements of the samples were conducted using a standard four-point probe van Der Pauw setup. The probe spacing was kept at 2 mm and the individual test was done multiple times in different directions at room temperature to make sure that the values were repeatable.

3 | RESULT AND DISCUSSION

3.1 | Thermodynamic preferences of particles localization

Estimating the interaction between polymer pairs and nanoparticles with each blend component predicts the thermodynamic preferences of nanoparticles for localization in polymer blends. According to Young’s equation, a filler’s location in binary polymeric blends can be estimated by calculating the wetting coefficient:

\[
-1 < \cos \theta < 1 = \omega = \frac{\gamma_{CA} - \gamma_{CB}}{\gamma_{AB}}, \tag{1}
\]

where \( \gamma_{CA} \) is the interfacial energy between filler and polymer A, and \( \gamma_{CB} \) is the interfacial energy between filler and polymer B and \( \gamma_{AB} \) is the interfacial energy between polymer A and B. If the wetting coefficient is higher than 1, the fillers are located in polymer B; when values are lower than \(-1\), they are located in polymer A, and if the wetting coefficient is between 1 and \(-1\), the fillers are preferentially located at the interface of polymer blends. Primarily two equations are used, including the harmonic-mean and geometric-mean equations, to calculate the interfacial energy from surface energies and their disperse and polar components (Table 2).

Harmonic mean equation:

\[
\gamma_{12} = \gamma_1 + \gamma_2 - 4 \left( \frac{\gamma_{1d}^{\ell} \gamma_{2d}^{p}}{\gamma_1^{d} + \gamma_2^{d}} + \frac{\gamma_{1p}^{\ell} \gamma_{2p}^{d}}{\gamma_1^{p} + \gamma_2^{p}} \right), \tag{2}
\]

where \( \gamma_i \) is the surface tension of component i, \( \gamma_i^{d} \) is the dispersive portion of the surface tension of component i, and \( \gamma_i^{p} \) is the polar portion of the surface tension of component i.

\( \gamma_{12} (\text{mN/m}) \) for PP/PA, PA/BN, PA/r-Go, and PP/r-Go is equal to 2.71, 8.26, 22.2, and 28.15, respectively.
Moreover, at the processing condition (240°C), the wetting coefficient ($\omega_a$) of PP/PA-BN and PP/PA-rGo is $-4.29$ and $-1.9$. The calculated values of the interfacial tension between components and the wetting coefficient data for the PP/PA blend clarified that both BN particles and rGo nanoplatelets should be preferentially located in the PA phase (Schematic 1).

### 3.2 Rheology

Figure 1 shows the results of storage modulus ($G'$) and complex viscosity ($\eta^*$) versus the frequencies obtained for PP, PA6, and the PP/PA6 blend (and their nanocomposites). As the figure shows, PP and PA6 both exhibit Rosian-type viscoelastic behavior, as well as terminal behavior of the storage modulus ($G'$) in the low-frequency range. Conversely, the PA6/BN composite exhibits nonterminal behavior and a highly enhanced storage modulus. This solid-like behavior of PA6/BN composites indicates that a percolated structure had formed between the BN particles. This phenomenon is illustrated by the SEM micrograph shown in Figure 2(A), (B). As can be seen, the BN particles are well dispersed in the PA matrix.

The PP/PA6-BN blend composite sample also shows a pronounced nonterminal behavior in the storage modulus ($G'$) and a sharp viscosity upturn in the low-frequency range, albeit with a lower elastic response than the PA6/BN composite. This result implies that the BN particles form a 3D network structure in the PA6 matrix phase of the PP/PA6-BN blend composite, whereas the unfilled PP phase provides the most significant contribution to the viscous part of this composite. This notion is supported by the SEM micrographs of PP/PA-BN shown in Figure 2(C). The micrographs depict a matrix-disperse-like morphology in which an elongated PP phase, in cylindrical form, is dispersed in the BN-filled matrix. The PP particles are also seen to be finely dispersed in the PA6 continuous phase.

Replacing 10% and 15% of BN by rGo in PP/PA-BN-rGo blend composite has a minor reduction effect on storage modulus ($G'$) at low frequencies. This phenomenon can be explained in terms of the BN network structure's disintegration in PA phase caused by rGo nanoplatelets. In other words, rGo nanoplatelets may locate between the BN particles and weaken the BN network structure. This effect is demonstrated in the FESEM micrographs of the hybrid-filled nanocomposite samples in the PA matrix shown in Figure 2(D),(E), with BN/rGo ratios 30/10 and 25/15, respectively. Comparing these micrographs to Figure 2(C), it is clear that the size of the PP dispersed phase increases as rGo content increases. Thus, the addition of 15% rGo (PP/PA6-BN-rGo 15)

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**Table 2** Surface energies and polarities of the polymers and fillers

| Component       | Total surface energy (mN/m) | Surface energy of disperse part (mN/m) | Surface energy of polar part (mN/m) |
|-----------------|-----------------------------|----------------------------------------|-----------------------------------|
| PA6             | 23.84                       | 20.64                                  | 3.34                              |
| PP              | 17.1                        | 16.7                                   | 0.36                              |
| Boron nitride   | 47.1                        | 35.8                                   | 11.3                              |
| Reduced graphene oxide | 31.20                    | 28.98                                  | 2.22                              |

Note: Values for PA, PP, GO, and BN are obtained from References [52–55], respectively. Abbreviations: BN, boron nitride; PA, polyamide; PP, polypropylene; rGo, reduced graphene oxide.

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Schematic 1: The microstructure of blend composites in different localization states based on thermodynamic parameters

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changes morphology from matrix-disperse into co-continuous morphology. This result indicates that rGo has preferentially remained in the PA phase, and no migration of rGo into the PP phase occurred. For precise observation, the PP phase in the PP/PA6-BN-rGo15 sample was etched out by xylene, and it can be seen that PA matrix phase forms a continuous structure (Figure 3).

The PP-rGo/PA6-BN nanocomposite sample that was prepared using the PP-rGo blend masterbatch exhibits a greater storage modulus ($G'$) than the PP/PA6-BN-rGo sample in the high-frequency range. This observation suggests that the rGo nano-platelets are mostly localized in the PP phase or at the PP/PA6 interface in the PP-rGo/PA6-BN nanocomposite. This is confirmed by the FESEM micrograph in Figure 2(F), which shows a coarsen or continuous-like morphology for the PP phase.

3.3 Thermal conductivity

The results of the thermal conductivity measurements are shown in Figure 4. As it is observed, neat PP and PA exhibit relatively low thermal conductivity—0.2 W m$^{-1}$ K$^{-1}$ and 0.28 W m$^{-1}$ K$^{-1}$, respectively.

The thermal conductivity of conductive-filled polymer composites is significantly enhanced when conductive fillers form a network structure in the matrix. As shown in Figure 5 in the PA6/BN sample, the addition of 40% BN conductive filler to the PA6 matrix phase improved the thermal conductivity from 0.28 to 1.5 W m$^{-1}$ K$^{-1}$. This indicates a 3D connected network structure between the BN particles, which is consistent with the SEM micrographs. The thermal conductivity of polymer-based composites is greatly influenced by the phonon scattering that occurs at the interfaces of the polymer matrix/conductive-fillers and polymer/polymer. Generally, strong interfacial interaction facilitates phonon transport across the interface and reduce phonon scattering.

Figure 4 displays that the thermal conductivity of the PP/PA6-BN composite is significantly lower than that of the PA6/BN sample. This was observed despite the 3D network structure of the BN particles localized in the PA matrix. Thus, it seems that the addition of PP to PA6/BN in the PP/PA6-BN sample adds new interfaces into the system, which increases phonon scattering. Therefore, the thermal conductivity of PP/PA6-BN remains low, even when BN formed a network in the PA phase. The same result was obtained in our previous study on the thermal conductivity of PA/cyclic olefin copolymer/BN blends.$^{[56]}$ A comparison between the PA/BN single-filled composite and the hybrid system showed a reduction in the thermal conductivity of the PA/BN composite with the addition of the second phase to the system.

Figure 4 illustrates replacing a fraction of the BN (10% and 15%) with rGo in the hybrid-filled samples PP/PA6-BN-rGo10 and PP/PA6-BN-rGo15 resulted in a considerable increase in thermal conductivity. In the hybrid system, replacing BN with rGo caused a phonon–electron interaction to occur. In other words, rGo nanoplatelets acted as heat-conductive bridges among the BN platelets, consequently contributing to creating a more effective percolating network for thermal conduction. This is in agreement with the rheological results, which showed an induced weakening effect on the storage modulus of the hybrid-filled composite as a result of the rGo nanoplatelets' placement between the BN particles. Figure 4 also shows that the PP-rGo/PA6-BN sample in which the rGo was first melt mixed with PP yielded much lower thermal conductivity than the hybrid-filled sample. This is mainly related to the loss of the interconnectivity between BN and rGo in the PA6 continuous phase. Neither rheological measurements nor the four-point test revealed any rGo network formation in the PP phase. In other words, the presence of rGo in this sample cannot provide a synergistic contribution effect on
thermal conductivity. Hence, it can be easily concluded that it is essential to have interconnectivity between hybrid fillers to show the synergistic effect on thermal conductivity.

Figure 4 shows that the thermal conductivity of PP-rGo/PA6-BN was higher than that of PP/PA6-BN; one reason for this could be the presence of rGo in the PP phase. On the other hand, the SEM micrographs in
Figure 2(C),(F) indicate that embedding rGo into the PP phase changed the morphology from matrix-disperse to co-continuous. The difference in the samples’ thermal conductivity could be explained by the lower total interface of the co-continuous morphology in comparison with matrix-disperse morphology. Hence, a change in morphology from matrix-disperse to co-continuous causes a decrease in phonon scattering, which leads to an increase in thermal conductivity. Specifically, the morphological change in PP-rGo/PA6-BN could be explained by the mechanism proposed by Filippone and Acierno,[57] on nanoparticle-induced promoting clustering effect, which could lead to changing morphology for PS/PMMA/nano caly blend.

As it can be seen from Schematic 2(A), in the PP/PA-BN sample, the BN forms a network structure in the PA phase. However, when both BN and rGo both added into the PA phase (PP/PA-BN-rGo 15), the BN and rGo hybrid network structure formed in the PA phase. As shown in the Schematic 2(B), the rGo’s platelets act as heat conductive bridges among BN platelets, and greatly contribute to the formation of a more efficient percolating network for thermal conduction. By comparing the thermal conductivity of the samples, it is obvious that using the hybrid fillers improves the heat conduction by forming hybrid 3D networks and has a synergistic effect on thermal conductivity of the PP/PA polymer blends.

To gain further insight into the effect of hybrid fillers on thermal conductivity, two prominent questions are proposed. First, what kind of arrangement of BN-rGo (BN-rGo-BN, BN-rGo-rGo-BN, rGo-BN-rGo, etc.) is desirable to have the highest synergistic effect of hybrid fillers. In other words, there is a desirable arrangement of BN-rGo in which the phonon–electron interaction is at its highest possible level while the composite remains its electrical insulation. The second question is that, by comparing the SEM images, it seems that adding rGo into the PA6/BN phase has changed the morphology of the whole system and affect the thermal conductivity by increasing or decreasing the total interface. So, it can be concluded that a certain amount of rGo is needed to benefit from it because it controls both the hybrid effect and morphology of the system.
3.4 Electrical conductivity

The filler network in smart composites is capable of dictating the electrical behavior in smart applications. Noteworthy, the free electrons in the carbonaceous filler, such as graphene platelets, are the critical criteria for providing an ideal smart thermally conductive product. By considering the final application, a high level of conductivity in graphene nano-platelets is not necessarily considered as a useful parameter because the increase in the electrical conductivity usually results in a sharp rise of the electronic part of thermal conductivity. In some electronic applications, for instance, increasing both electrical and thermal conductivity is not required for thermal management. In this case, conductive graphene nanoparticles have been used to increase the relative conductivity. However, BN platelets cause a severe decrease in electrical conductivity strength due to interrupting the conductive path. Another decisive parameter is filler localization, where the filler was embedded, as mentioned earlier. The electrical conductivity ($\sigma$) of PP/PA and its composites are studied, and the results are reported in Figure 5. The $\sigma$ depends strongly on the localization and content of the filler. The rate of change in the conductivity in blend composites containing carbonic filler is notably higher than that for the ceramic-based blend composites because of enhancing electron mobility. As seen in this figure, by replacing a small amount of rGo instead of BN, the electrical conductivity of PP/PA-BN-rGo has increased due to the existence of rGo obstacles between BN platelets. However, the BN percolated structure do not let the rGo to make the electrically conductive pathways. For the PP-rGo/PA-BN sample, the presence of rGo in the PP phase led to a slight increment in electrical conductivity. However, in this case, the content of rGo is low, so that rGo was not able to form electrically conductive pathways.

The rheological features of blend composites were tested, and then the thermal and electrical behavior of samples was also tracked. It should also be noted that the thermoelectrical properties of resultant blend composite improved after introducing both BN and rGo, thus, eventually suggesting this sample is astonishing properties for numerous electronic applications.

4 CONCLUSION

The thermal conductivity of PA6/PP blends containing BN and rGo as hybrid fillers were studied, and the results were compared with a PA6 single BN-filled sample. A masterbatch feeding route was employed to localize the conductive fillers in the PA6 matrix, and thermal conductive composites were prepared by melt mixing. Rheological results and SEM micrographs revealed that the conductive fillers rGo and BN were localized in the PA6 matrix and formed a percolated network structure by utilizing a masterbatch feeding method. The single BN-filled sample, PP/PA6-BN, showed significantly lower thermal conductivity than PA6/BN. This deduction can be explained by interfacial thermal resistance or phonon scattering. However, replacing a fraction of the BN with rGo in the PP/PA6-BN-rGo10 and PP/PA6-BN-rGo15 samples had synergistically affected the thermal conductivity of the samples, implying that rGo may act as a heat-conductive bridge between BN particles. The PP-rGo/PA6-BN sample in which rGo was localized in the PP phase yielded a lower thermal conductivity than PP/
PA6-BN-rGo10 and PP/PA6-BN-rGo15 because of the loss BN-rGo interconnectivity. Moreover, the localization of rGo in the PP phase changed the morphology from matrix-disperse into co-continuous, which led to a decrease in phonon scattering.

CONFLICT OF INTEREST
The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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