

Processing, Properties and Structure of Exfoliated Graphite Nanoplatelet-Polypropylene Nanocomposites

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Abstract

This research explores the potential of using exfoliated graphite nanoplatelets (graphene sheets ~10nm thickness, ~1 μ m diameter), a new multifunctional material developed in MSU, as reinforcement in polypropylene. The goal is: (i) to fabricate exfoliated graphite nanoplatelet (xGnP)-polypropylene (PP) nanocomposites and determine their mechanical, thermal and electrical properties (ii) to compare xGnP-PP nanocomposites to composites made using other carbon-based electrically conductive fillers, (iii) to understand the processing-property relationship and (iv) to investigate how addition of xGnP alters the crystallization and melting behavior of polyolefin composites. xGnP-PP nanocomposites were fabricated in a two-step process; compounding (by melt mixing, solution method and solid state premixing) and molding (injection or compression). The xGnP is characterized using Transmission Electron Microscopy (TEM), and Environmental Scanning Electron Microscopy (ESEM) is used to quantify the morphology and the fracture surface of the nanocomposites. Results include thermal (coefficient of thermal expansion and thermal conductivity), and mechanical properties (flexural strength, modulus of elasticity). In addition, the electrical conductivity and the percolation threshold of the xGnP-polypropylene nanocomposites will be determined as a function of the xGnP's aspect ratio and the processing method used. Finally, the effect of xGnP on the crystallinity of neat PP is explored using Differential Scanning Calorimetry (DSC), XRD, and optical microscopy.

INTRODUCTION

Layered silicates are the first nanoreinforcement used in polymeric matrices that have been studied systematically since the 1980's [1,2]. Clay nanocomposites show enhanced mechanical properties such as strength and modulus accompanied by an increase in impact strength and storage modulus [3, 4]. The heat distortion temperature increases and there is significant reduction of water adsorption [5, 6, 7]. Furthermore, clay nanocomposites show also improved barrier properties [8, 9], due to the platelet structure and the large aspect ratio of silicate layers, display a significant increase in heat resistance and thermal stability and show self-distinguishing characteristics [10]. In addition, silicates act as a nucleating agent for crystallization leading to smaller spherulite size improving thus the impact strength of nanocomposites [11]. However, the clay nanocomposites lack electrical and thermal conductivity that limits their potential applications.

Recently, there is an increased interest of using organic materials such as carbon black, carbon fibers and nanotubes as reinforcements for polymers due mainly to their superior thermal and electrical properties. Carbon nanotubes are potentially ideal nanoreinforcements since they combine high aspect ratio, electrical and thermal conductivity and have excellent stiffness and strength, and low density [12]. However, their high price makes the nanotube reinforced polymers too costly for most applications.

Besides layered silicate nanoclays and carbon nanotubes, graphite platelets are also among the leading nano-scale fillers in research and development and commercial projects [13]. Although xGnP nanocomposites have not received as much attention as carbon nanotubes, research in the Drzal group [14] has shown that they can be a cost effective alternative to carbon nanotubes and provide excellent competitive functional properties. They combine the layered structure and low price of clays and the superior electrical and thermal properties of nanotubes. There is a wide variation of the properties of the xGnP-polymer nanocomposites depending on the origin (kind of graphite intercalated compound used), form (intercalation or degree of exfoliation), morphology and aspect ratio of graphite used, as well as on the fabrication method. The xGnP nanocomposites can be used not only for structural and packaging applications but also for electrostatic dissipation, (ED), electromagnetic and radio frequency interference shielding (EMI, RI), and heat dissipation.

In this study the exfoliated graphite nanoplatelets are produced by a special thermal treatment. The xGnP-PP nanocomposites were fabricated by compounding using various methods i.e., melt mixing, solution approach and premixing and molding, injection or compression. The degree of graphite's exfoliation and the morphology of the nanocomposites were characterized by TEM and ESEM respectively. The mechanical, thermal and electrical properties were determined as a function of xGnP loading and aspect ratio.

EXPERIMENTAL

Materials

The polymer used is polypropylene powder (Pro-fax 6301, melt flow index 12 g/10min, ASTM D1238), which was kindly provided by Basell. The control carbon materials used for comparison with the xGnP were (i) PAN based carbon fiber (PANEX 33 MC Milled Carbon Fibers, Zoltek Co), (ii) VGCF (Pyrograf III, PR-19 PS grade, Pyrograf Products, Inc.) and (iii) nanosize High Structure carbon black (KETJENBLACK EC-600 JD, Akzo Novel Polymer Chemicals LLC). The geometrical and surface characteristics of all the reinforcements used are given in Table 1.

The exfoliated graphite nanoflakes (xGnP) were made using Graphite Intercalated Compounds (GICs) obtained from UCAR International Inc. The sulfuric acid-based intercalated graphite, shown in Figure 1a, is heated by microwave, a cost and time effective exfoliation

process initially proposed by Fukushima [14]. The residual intercalates that are trapped inside the graphite galleries vaporize resulting in significant expansion (~500 times) of the graphite flakes as shown in Figure 1b. Ultrasonic pulverization is applied to break down the worm-like structure and obtain individual graphite sheets that are less than 10nm thick with a diameter of ~15µm. Their diameter can be further reduced by milling with a vibratory mill, resulting thus in nanoflakes with diameter less than 1µm. These two types of graphite differ in aspect ratio and are shown in Figures 2a and 2b respectively. The thickness of the nanoflakes was determined using TEM and is indicated in Figure 3 that shows two adjacent nanoplatelets with an average thickness of ~5nm. Each nanoplatelet consists of more than 10 graphene sheets.

Table 1: Characteristics Of The Conductive Fillers Used

Material	Length (µm)	Diameter (nm)	Aspect Ratio	Surface Area (m ² /g)	Elec Resistivity (uohm cm)
xGnP-1	>0.01	860	~77	94	100 ^[15-16]
xGnP-15	>0.01	1500	~150	105	100
PAN CF	175	7200	~24	16	1400 ^[16]
VGCF	50-100	150	350-650	25	55 ^[17]
CB	0.4-0.5	400-500	1	1400	10 ⁴ -10 ⁵ ^[16]

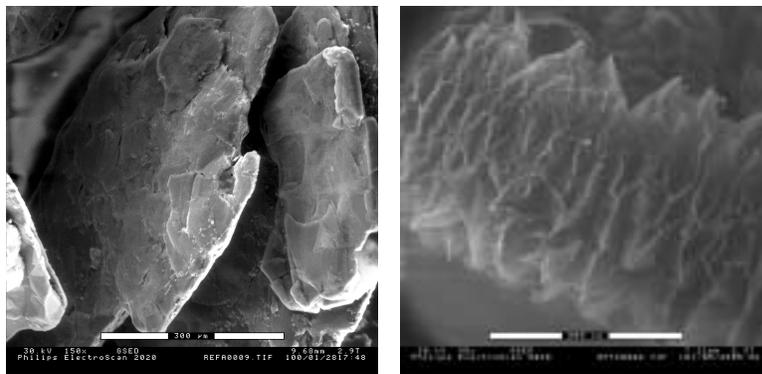


Figure 1. ESEM micrographs of a) as received acid intercalated graphite (scale bar 300µm), and b) expanded graphite(scale bar 500µm)

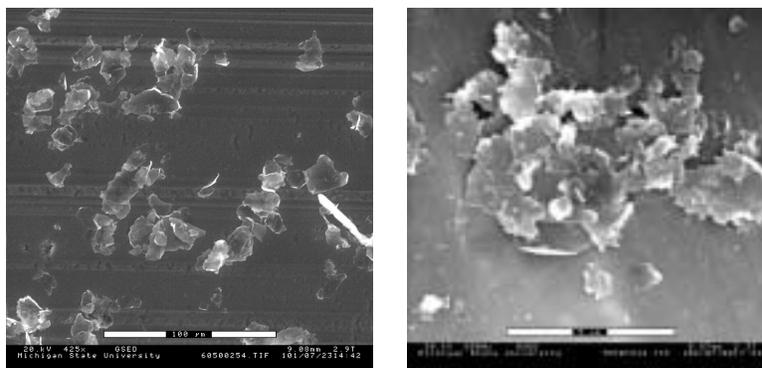


Figure 2. ESEM micrographs of a) pulverized graphite nanoflakes 15µm, xGnP-15 (scale bar 100µm), and b) milled graphite nanoflakes 1µm, xGnP-1 (scale bar 5µm)

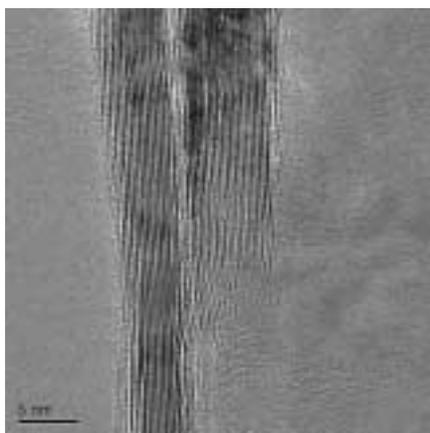


Figure 3. HRTEM Image of the top view of xGnP-1, scale bar is 5nm

Processing

Melt Mixing Approach

The main processing method used in this study is melt mixing due to its simplicity and compatibility with existing polymer processing techniques such as extrusion, injection and compression molding. A DSM Micro 15cc Compounder, (vertical, co-rotating twin-screw microextruder) was used. The processing conditions used are 180 °C for 3 minutes at a screw speed of 200 rpm.

Solution Approach

A limited number of samples were also fabricated using solution approach. The process used here is a modified version of the one proposed by Shen *et al* [18]. The graphite nanoplatelets were dispersed in xylene using sonication for 2hrs and the PP was dissolved in refluxing xylene at 130 °C for 0.5 hrs using reflux. The graphite suspension was added to the PP solution and after refluxing for 1.5hrs the heating was stopped and a portion of xylene was extracted by filtration. When the temperature dropped to 70 °C the mixture was precipitated by addition of acetone, filtered, and dried under vacuum. The resulting composite powder was used for compression and injection molding.

Premixing Approach

In case of polypropylene, the solution approach requires large amounts of solvents i.e., xylene and high temperatures that are neither practical nor safe. For this reason a new compounding method developed in our lab, is proposed in this study. The xGnP is dispersed in isopropyl alcohol (IPA) by sonication for 1 hour at room temperature, the PP powder is added to the solution and the sonication is continued for 0.5 hrs. The IPA is removed by heating at 80°C or can be filtered and recycled. The result is PP particles that are homogeneously coated with xGnP. ESEM micrographs of xGnP coated PP at a 0.2wt% loading of xGnP is shown in Figure 4.

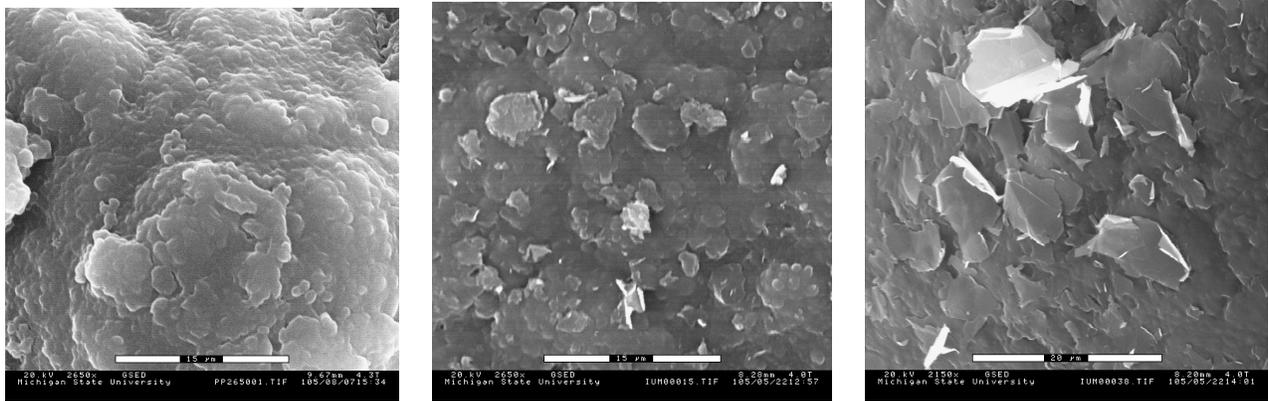


Figure 4. xGnP-coated PP, (i) neat PP particle (15um), (ii) xGnP-1 coated PP (15um) and (iii) xGnP-15 coated PP (20um)

The injection-molded samples were made using a Daca Micro Injector. The cylinder temperature was 180 °C and the mold temperature used was 80 °C. An injection pressure of 160 psi was used. The compression-molded samples were made using the composite pellets made by extrusion. The conditions used are at 200 °C for 20 minutes no pressure applied and 200 °C for 20 minutes under pressure ~ 50.44 tonnes/cm². During the compression molding vacuum was applying to remove any trapped air.

RESULTS

Mechanical Properties

The flexural strength and modulus of elasticity of various polypropylene composites up to a loading level of 20 vol% is shown in Figures 5 and 6 respectively. The samples are made by melt mixing and injection molding. In case of carbon black the maximum loading is 5 vol% because at higher loadings the viscosity increased significantly and the material did not flow out of the extruder die. Although, all the reinforcements improved the strength, xGnP-1 had the most profound effect up to a loading of 5 vol% resulting in $\sim 36\%$ increase of the flexural strength compare to that of the neat polypropylene. Carbon black composites (up to 5 vol%) show also similar improvement. At higher loadings both VGCF and PAN based CF show significant improvement of the strength. In particular, addition of 20 vol% of PAN based CF results in a strength increase of 110% while addition of the same amount of xGnP-1 improves the strength only by 57%. The fact that as the xGnP-1 content increases i.e., above 10 vol% the strength reaches a plateau indicates insufficient dispersion of the graphite nano-platelets in the polymer matrix and the need for a surface treatment that will improve the adhesion between the polymer and the graphite and result in a well-dispersed system.

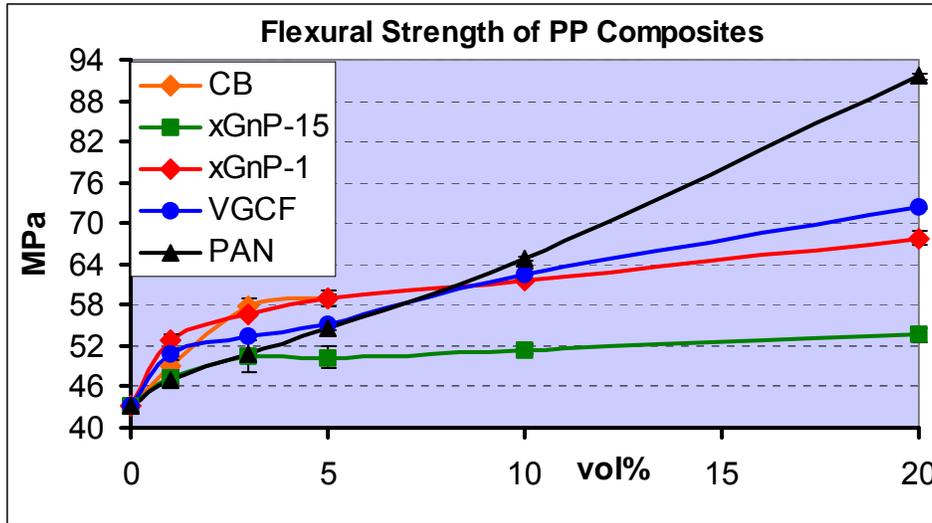


Figure 5. Flexural strength of various PP composites

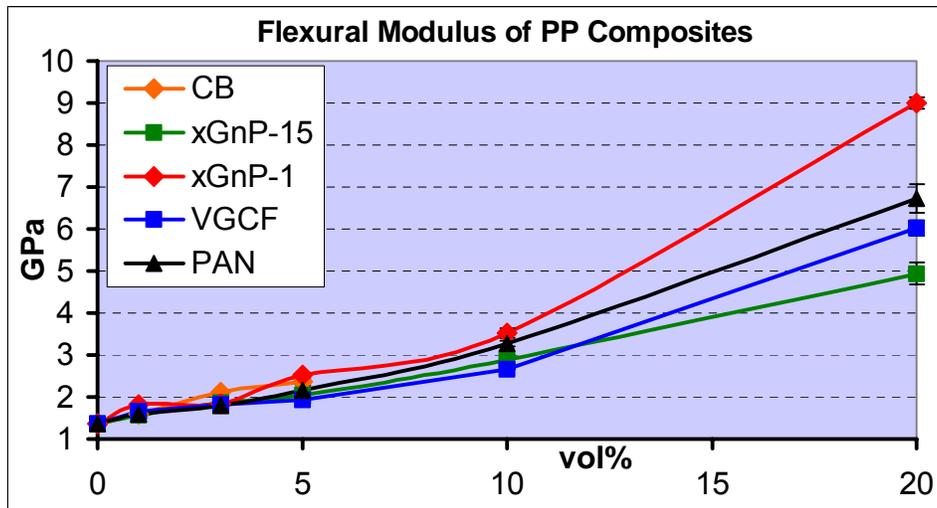


Figure 6. Modulus of Elasticity of various PP nanocomposites

Figure 6 shows the modulus of elasticity of the various polypropylene composites. The results indicate that the best reinforcement is xGnP-1 increasing the modulus ~30% at a loading of 1 vol% and by 560% at a loading of 20 vol%, followed by PAN based CF (enhancement of modulus 400% at a loading of 20 vol%) with VGCF having a less significant effect on the modulus of the neat polymer. Addition of xGnP-15 also improves the flexural modulus of PP at all loadings used but not dramatically which indicates poor dispersion as shown also by morphological study performed by ESEM.

Thermal Properties

The coefficient of thermal expansion (CTE) of xGnP-PP composites at 3 vol% was determined by TMA for two temperature regimes below and above the glass transition temperature. CTE was measured along two directions, the transverse, which is the direction perpendicular to the direction that the polymer melt flows into the mold, and the longitudinal, which is the direction along the flow. The results are shown in Figures 7 and 8 respectively. Decrease of the CTE along the longitudinal direction was observed for all the fillers at both below and above T_g . The xGnP-1 had the same effect with VGCF and PAN based carbon fibers, ~25% decrease of CTE in the regime below T_g . For the above T_g regime, graphite had the same effect as carbon black and VGCF (~40% decrease) but PAN based carbon fiber had a more dramatic effect. The same trend was observed also in the measurements of CTE along the transverse direction as shown in Figure 8. The xGnP resulted in a decrease of CTE of the order of 15-20%. A similar decrease was observed also in the VGCF-polypropylene composites.

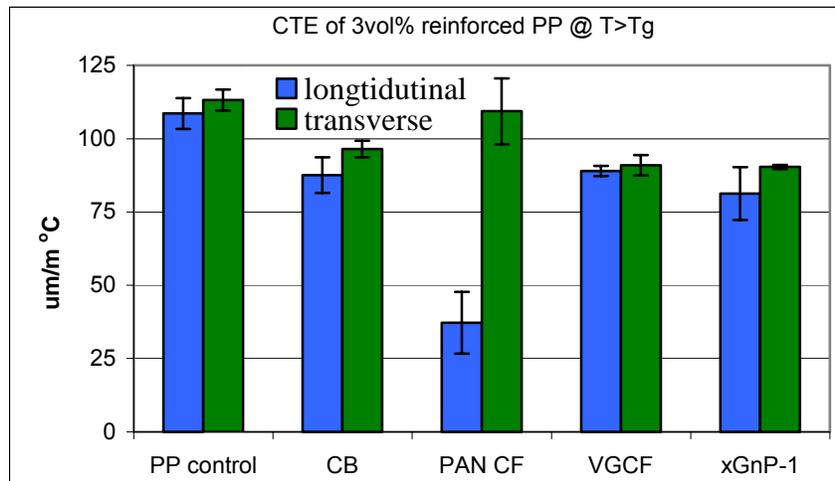


Figure 7. CTE of polypropylene nanocomposites along the flow direction

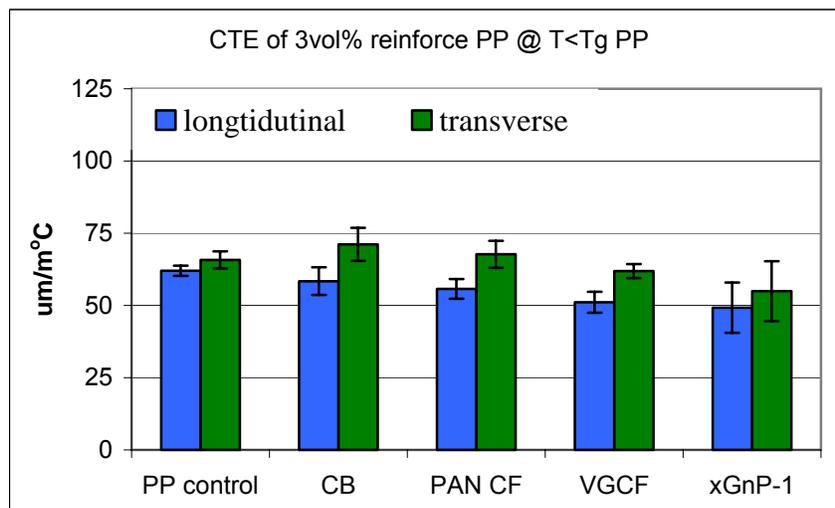


Figure 8. CTE of polypropylene nanocomposites along the flow direction

The advantage of xGnP over clays is the superior thermal and electrical properties of graphite. A study on thermally conductive graphite-nylon 6,6 composites demonstrated that (i) by increasing the amount of graphite the through plane conductivity increased significantly, and (ii) the in-plane thermal conductivity is ~3 times larger than the through plane conductivity due to orientation during injection molding and the anisotropy of the fillers [19]. In this study only the through plane thermal conductivity was measured using dynamic scanning calorimetry (DSC). The samples tested were disks (diameter of 5mm, and thickness~0.5mm) cut from the middle section of rectangular bars made by melt mixing and injection molding. Samples at various xGnP loadings and using both sizes of nanographite were tested in order to study the effect of graphite loading and aspect ratio on the thermal conductivity. The results are shown in Figure 9. It is expected that xGnP-15 due to their larger size they will result in higher thermal conductivity since the interface is smaller and heat loss due to scattering is less. However, no significant effect of the aspect ratio was observed at the xGnP loadings tested. A possible reason is that due to processing xGnP-15 do not maintain their platelet morphology and tend to form large agglomerates as shown by ESEM, which both result in heat scattering and thus reduced thermal conductivity.

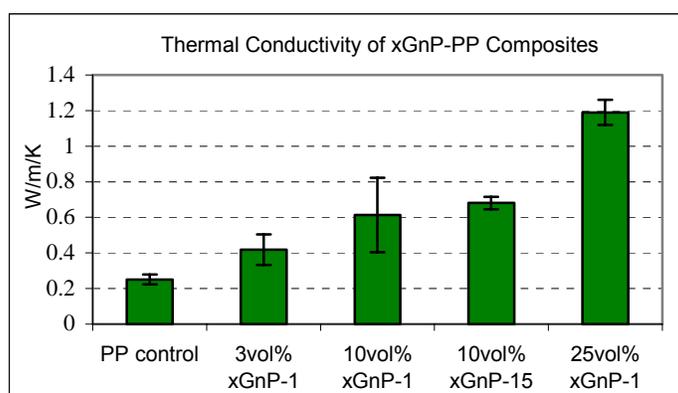


Figure 9. Thermal conductivity of xGnP-1 and xGnP-15um -PP composites

Electrical Conductivity and Percolation Threshold

The important properties in electrically conductive composites are (i) the electrical conductivity, measured in S/cm and (ii) the percolation threshold, defined as the minimum volume content of the conductive reinforcement above which the polymer composite becomes electrically conductive. Both properties are the result of interactions of various factors such as the filler's volume fraction, distribution, size, shape, orientation and spacing of the filler within the polymer matrix and the conductivities and surface energies of the constituents. Other important factors are the crystallinity of the polymer matrix, the fabrication method and processing conditions.

One of the objectives of this research is to understand the effect that each one of the above-mentioned factors has on the conductivity and percolation threshold of the PP

nanocomposites and explore ways to lower the percolation threshold. The electrical conductivity of the injection molded polypropylene based composites was measured along the flow direction using a two-probe method. Samples with dimensions of 5x3x12 mm³ were cut from the middle portion of flexural bars, treated with O₂ plasma (10min, 550W) and gold coated to ensure good contact of the sample surface with the electrodes.

Effect Of Filler's Geometry And Conductivity

The percolation threshold and the electrical conductivity for various filler contents are shown in Figure 10. Carbon black percolates at less than 2 vol%. The percolation threshold for the other reinforcements are, ~5vol% for VGCF, 5vol% for PAN based carbon fibers, and ~8 vol% and 5vol% for xGnP-1 and xGnP-15 respectively.

Our results are in good agreement with the theory. The percolation threshold declines with decreasing particle diameter [20, 21] in case of spherical particles because as their size is reduced the interparticle distance increases so the formation of a continuous conductive path becomes more difficult. However, the carbon black used in this study does not consist of individual spherical particles but it is highly agglomerated (highly structured) with a high degree of porosity that allows for polymer penetration and may create a conductive network by occupying a large occluded volume at low concentrations. In case of non-spherical particles, as the aspect ratio of the conductive fillers increases the critical concentration to induce bulk conductivity in the composite reduces significantly [19]. That is, the large aspect ratio particles can still maintain point-to-point contact at low concentrations and allow for electron tunneling based on which electrons may pass through thin, insulating films at field strengths encountered in the gaps between adjacent conductive particles [22]. The effect of aspect ratio on lowering the percolation threshold is obvious in case of the carbon fibers used. VGCF with an aspect ratio of ~350-650 percolates at ~5vol% while the shorter PAN carbon fibers (aspect ratio of ~24) percolate at ~8vol%.

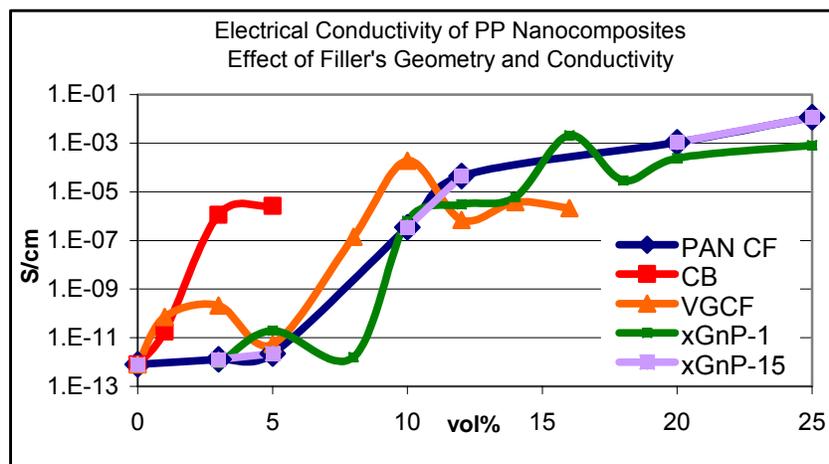


Figure 10. Electrical conductivity of PP nanocomposites-Effect of filler's geometry and conductivity

Effect Of Filler's Aspect Ratio

In order to study only the effect of the aspect ratio on the percolation threshold and conductivity of the composites two types of xGnP were used. Both are platelets of the same thickness (~10nm), which means same geometry, but they have different diameter; one is xGnP-15um (aspect ratio ~150) and the other is xGnP-1um (aspect ratio <100). The results are shown in Figure 11. The electrical conductivity of both the xGnP-15um (■ data point) and the xGnP-1um (◇ data point) injection molded (IM) samples seems to take off at ~7vol%. It is noted also that the xGnP-15/PP composites show higher conductivity than the xGnP-1/PP composites at higher loadings (>12vol%). The reason might be that the conductive path in the case of the high aspect ratio graphite consists of fewer but larger platelets so it has fewer discontinuities, which means less resistance.

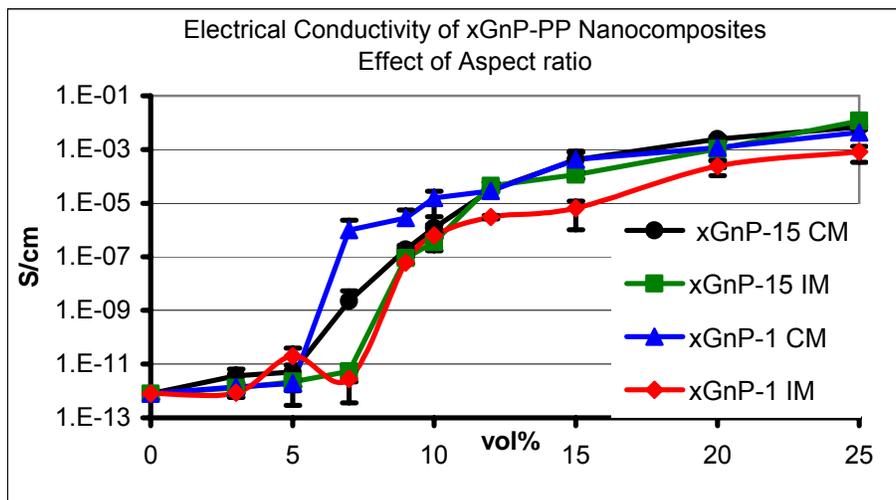


Figure 11. Electrical conductivity of xGnP-PP-Effect of aspect ratio

Based on the theory it is expected that the xGnP-15um will percolate at lower loadings since the larger the aspect ratio the easier it is to form a continuous conductive path. The reason that there is no effect of the xGnP aspect's ratio is that as indicated by ESEM investigation, there is not good dispersion of xGnP-15 in PP but it forms large agglomerates, shown in Figure 12a, and in addition, xGnP-15 tend to "roll up" inside the polymer matrix shown, in Figure 12b. Both of this phenomena result in reduction of the effective aspect ratio.



Figure 12: ESEM Image of a) graphite agglomerate in a 1 vol% xGnP-15-PP (scale bar 50 μm) and b) “roll-up” of xGnP-15 in 1vol% xGnP-15-PP (scale bar 10 μm)

Effect Of Filler’s Orientation and Anisotropy

The effect of filler’s alignment introduced during processing was also studied by fabricating the samples using two different methods: (i) extrusion-injection molding (IM), that introduces alignment of the graphite flakes along the flow direction [23] and (ii) extrusion-compression molding (CM), which results in random orientation of xGnP within the polymer matrix. The results are shown in Figure 11. For both types of graphite (xGnP-1 and xGnP-15 μm) the compression molded samples (CM), show lower percolation threshold i.e., 5vol% than the injection molded (IM) ones which percolate at 7vol%, because the random orientation of the filler during compression facilitates the formation of the conductive network. The xGnP alignment along the flow in the case of injection-molded samples was confirmed by ESEM study of the composites morphology and is shown in Figure 13.



Figure 13: ESEM Image showing the orientation and agglomeration of xGnP-15 in 1 vol% xGnP-15/PP composite made by melt mixing and injection molding (scale bar 500 μm)

In order to experimentally determine the effect of graphite's anisotropy and flow conditions on electrical conductivity and percolation threshold, two molds of different shapes were used. One was rectangular with an end gate along the length direction and the other was a disk shape mold with the gate placed at the periphery. The results are shown in Figure 14. The disk shape samples show higher percolation threshold and lower conductivity which is expected since in these samples the conductivity is measured through the plane, i.e., along the c-axis of the graphite plane.

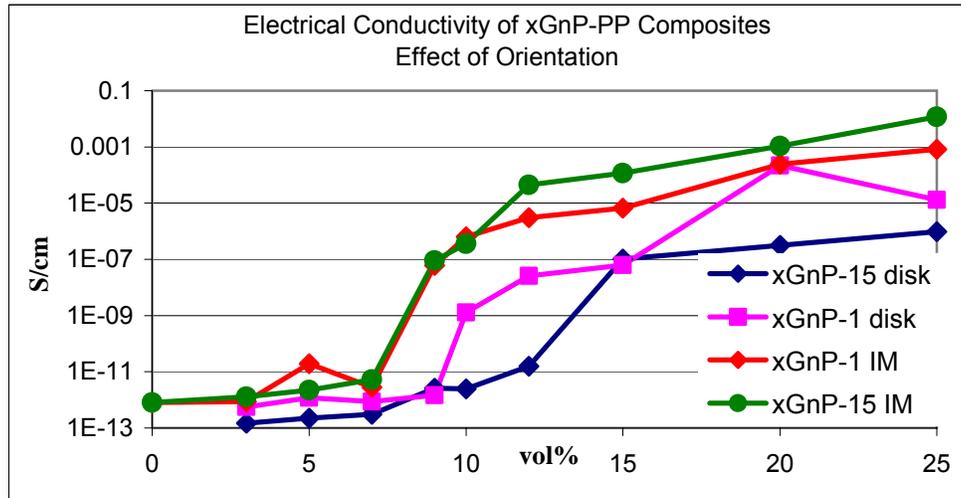


Figure 14: Electrical conductivity of xGnP-PP-Effect of xGnP's Orientation

Effect of Compounding

The orientation, dispersion and spacing of the conductive filler within the polymer matrix as well as the interactions between filler and matrix are critical factors for the conductivity and percolation threshold of the composites and are strongly affected by the processing method used to fabricate the composites. For example *in situ* polymerization [24] yields composites with a threshold of ~1vol% while same composites made by melt mixing [25] method percolate at ~6-9vol%. Comparison of melt mixing and solution intercalation method [18, 26] for fabrication of graphite-maleic anhydride grafted polypropylene, (gPP), nanocomposites indicates that solution intercalation lowers the percolation threshold. The explanation provided is that gPP molecules disentangled in the solution, and through physical adsorption into the pores and interplanar spaces of expanded graphite support and fix the graphite-gPP networks and maintain the high aspect ratio of the graphite sheets.

The effect of compounding on the percolation threshold and electrical conductivity of xGnP-PP nanocomposites was assessed by making samples using three different compounding methods: (i) melt mixing, (ii) solution i.e., dissolve PP in xylene and (iii) premixing i.e., disperse both xGnP and PP in isopropyl alcohol. Once the compounding was completed the samples were made by compression molding. The results are shown in Figure 15. The conductivity of xGnP-1/PP nanocomposites made by premix or solution compounding method is as high as 10^{-4} S/cm at a xGnP loading of 3vol%. This indicates that the percolation threshold is less than 3vol%.

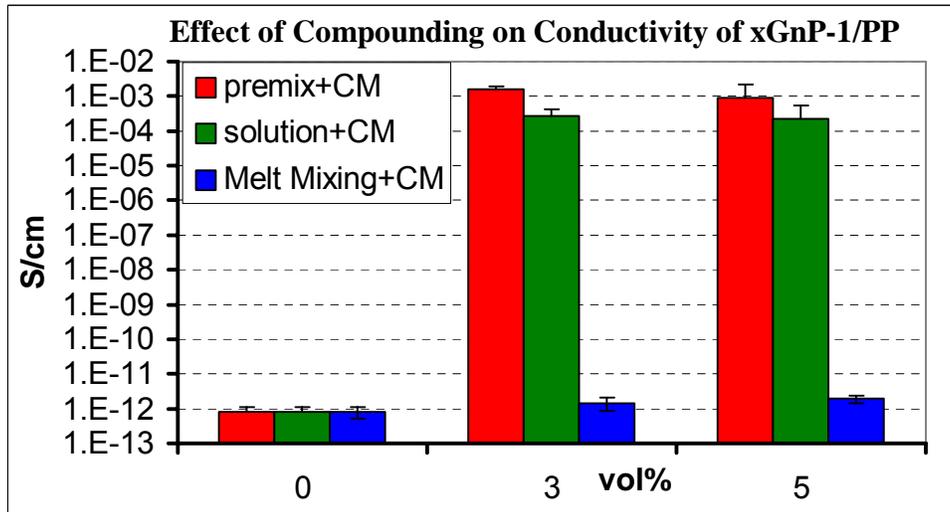


Figure 15. Electrical conductivity of xGnP-1/PP nanocomposites-Effect of compounding

The effect of compounding was further investigated using xGnP-15 and injection instead of compression molding. Since the premixed compounding method proved to be as effective as the commonly used solution approach in terms of electrical conductivity the solution method was not used further due to the prohibiting large solvent volumes. As shown in Figure 16 the premixed composites have a percolation threshold of ~5vol% while the samples made by melt mixing percolate at ~7.5vol%. This is probably due to the fact that the shear during the extrusion is not enough to break the xGnP-15 agglomerates thus more filler is required to form a conductive path. In addition the presence of agglomerates means that the aspect ratio is reduced resulting in an increased percolation threshold. However, once the percolation threshold is reached there is no significant difference between the two compounding methods i.e., at loadings above 20vol% the concentration of xGnP is so high that premixing is sufficient to prevent agglomeration.

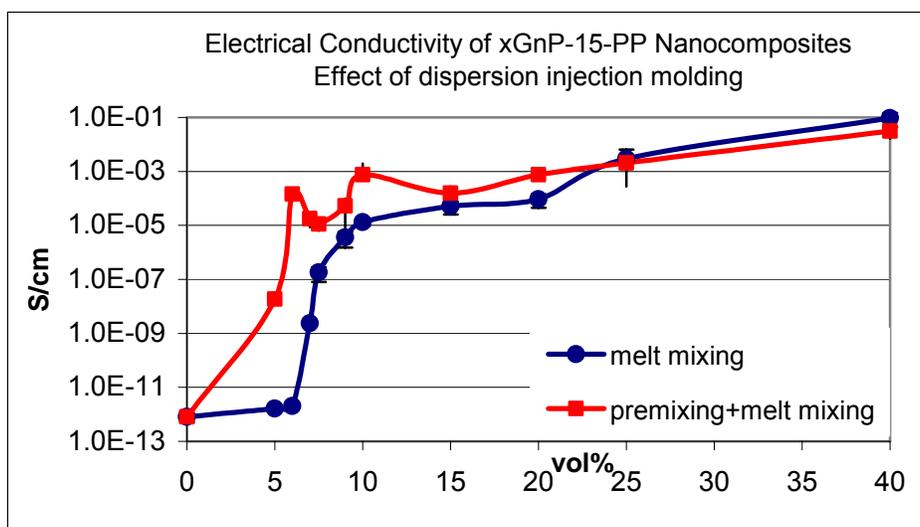


Figure 16. Electrical conductivity of xGnP-15/PP nanocomposites-Effect of compounding

Effect Of Crystallinity on Percolation Threshold

The crystallinity of the matrix is also a critical factor for the conductivity and percolation threshold of composites. For example in a highly crystalline matrix the formation of the continuous conductive path is easier compared to a less crystalline polymer where the higher amorphous portion may result in more homogeneous particle distribution [27]. Our results agree with the theoretical predictions. As shown in Figure 17 xGnP-1/PP nanocomposites made by premixing and compression molding have a higher conductivity at a loading of 0.1vol% when they are cooled slowly i.e., at $\sim 0.3^{\circ}\text{C}/\text{min}$ indicating that the percolation threshold is lower, while xGnP-1/PP composites made the same way but cooled fast i.e., at a rate of $20^{\circ}\text{C}/\text{min}$ have lower conductivity. Preliminary results obtained by DSC indicate that in the case of the slow cooled composites the degree of crystallinity is higher which justifies the differences in conductivity.

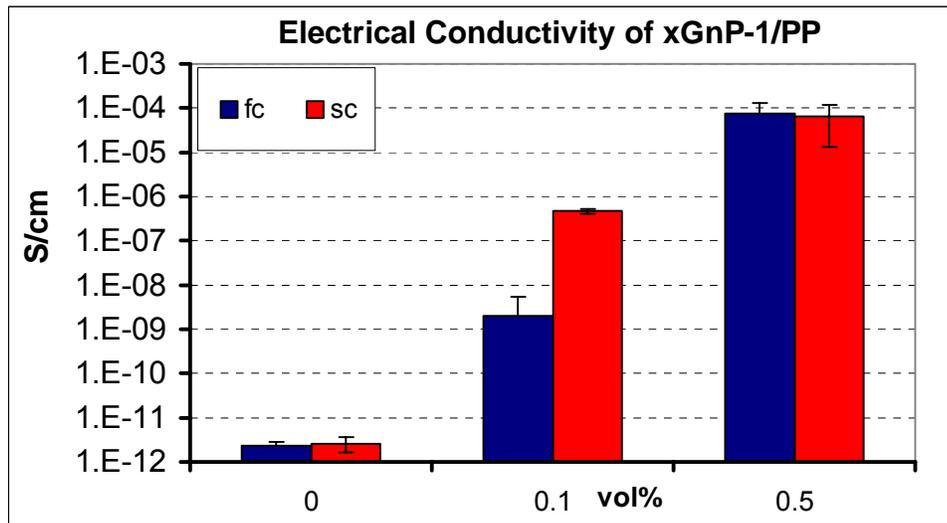


Figure 17. Effect of cooling rate on the electrical conductivity of xGnP-1/PP nanocomposites

Crystallinity Study of xGnP-PP Nanocomposites

Processing method and conditions as well as the existence of a second phase i.e., graphite in case of semicrystalline polymers like PP, might alter the crystallization behavior i.e., degree of crystallinity, crystallization temperature and rate, size or type of crystallites. Any change in any of the above parameters will affect the mechanical and barrier properties, as well as, the overall performance of the nanocomposites. In this study the effect of graphite on the crystallinity of polypropylene was studied using DSC, optical microscopy and XRD.

An optical microscope equipped with a hot stage was used to record the isothermal crystallization of graphite-polypropylene nanocomposites. The samples were initially heated up to the melting point in order to erase the thermal history (220°C at a rate of $20^{\circ}\text{C}/\text{min}$, for 10min) and then cooled down to the desired crystallization temperature. The magnification

used is 20X. Figures 18 and 19, are optical micrographs of isothermal crystallization at 130°C of neat PP and 0.01vol% xGnP-1/PP respectively.

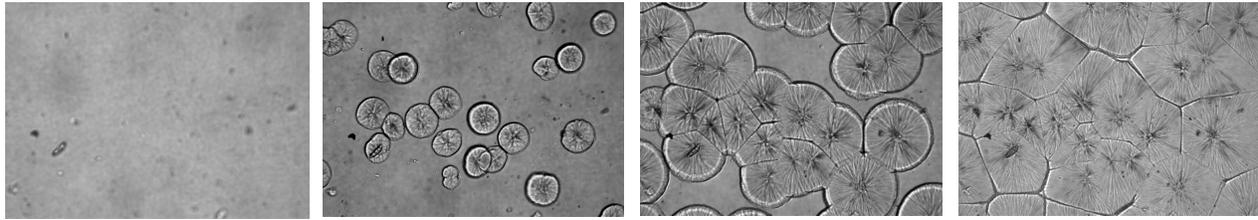


Figure 18. Isothermal crystallization of PP at 130°C after a) 0min, b) 5min, c)10 and d)20min

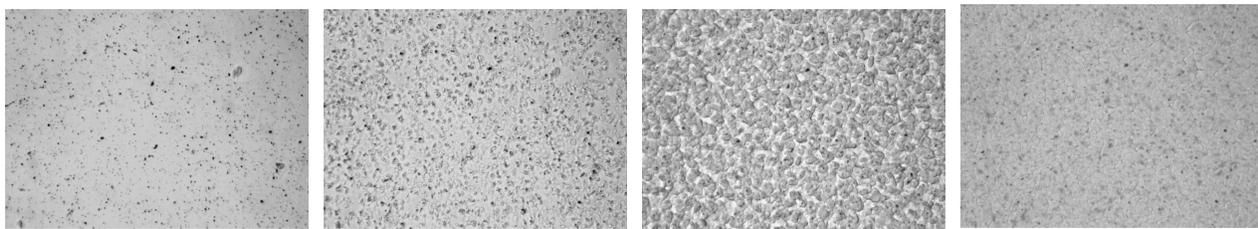


Figure 19. Isothermal crystallization of 0.01vol% xGnP-1/PP at 130°C after a) 0min, b) 1min, c) 2min and d) 5min

The addition of only 0.01vol% of xGnP-1 μ m causes significant changes in the crystallization of polypropylene, it accelerates the nucleation and growth of spherulites, i.e., crystallization in neat PP is completed in 20min whereas in the case of xGnP-PP it takes less than 3min. Once the nucleii are formed they keep growing without any secondary nucleation to take place. With addition of xGnP, the number of spherulites increases and their size get smaller. In terms of mechanical properties, smaller crystals mean higher impact strength.

The effect that xGnP has on the degree of crystallinity, the crystallization and melting temperature was determined by DSC. As shown in Figure 20 addition of xGnP slightly decreases the degree of crystallinity from 64% to 57% for a loading of 3vol%. Further increase of xGnP concentration does not really affect the degree of crystallinity. The melting point is also increased slightly with addition of xGnP as shown in Figure 21 but the most significant change is observed for the crystallization temperature which increases significantly i.e., $T_c=116.4^\circ\text{C}$ for neat PP increases to $T_c=127.4^\circ\text{C}$ and $T_c=134^\circ\text{C}$ for 1 and 10vol% of xGnP-1 respectively, indicating the strong nucleating effect of xGnP.

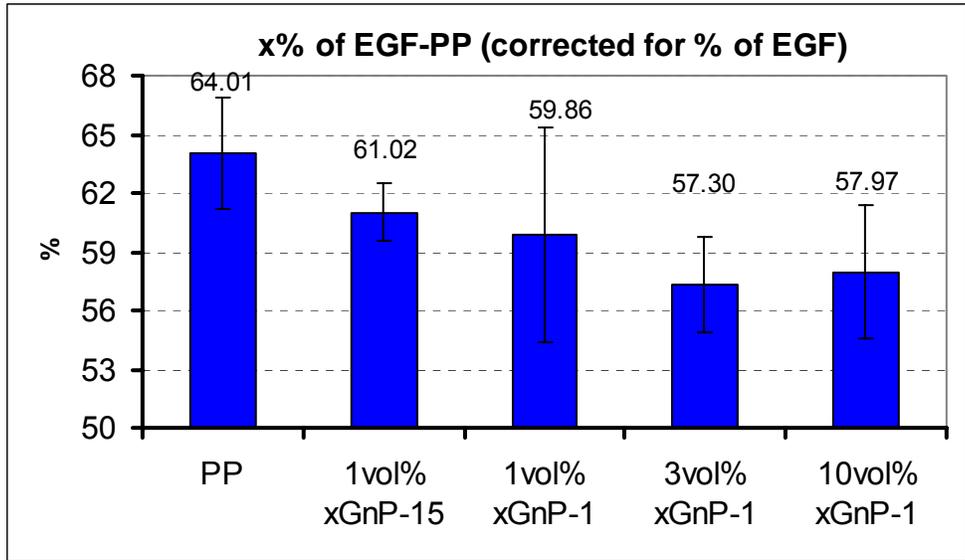


Figure 20. Degree of crystallinity of xGnP-PP measured by DSC

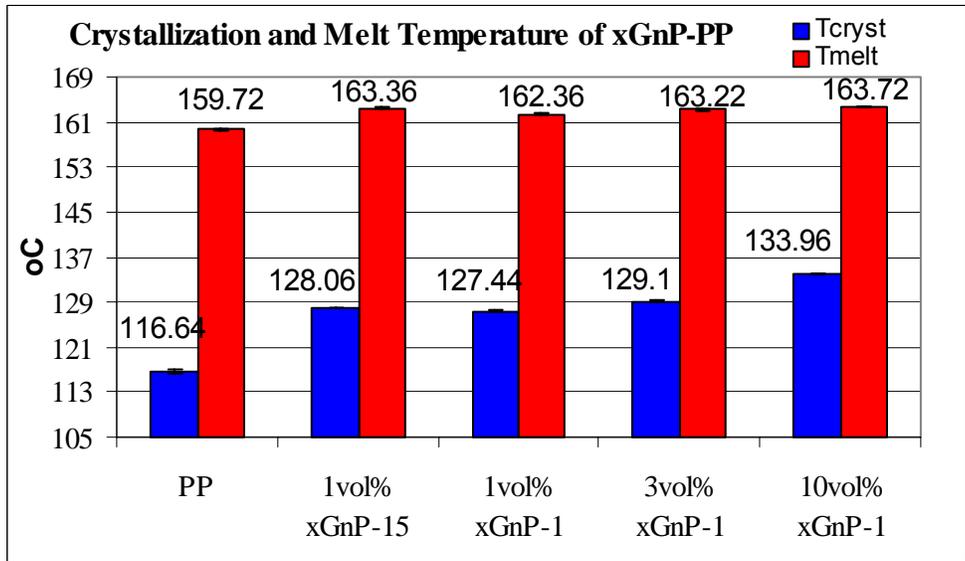


Figure 21. Melting and crystallization temperatures for xGnP-PP

Possible changes in the forms of PP crystals due the presence of xGnP were explored using XRD. The characteristic XRD (Cu Ka_{1, 2}) pattern of neat PP are peaks at 14, 17, 18.5 and 21.5 degrees (2theta) for the α -form of crystal and for the β -form two peaks at 16 and 21 degrees [28]. As indicated in Figure 22 the β -form peaks are absent from the XRD pattern of PP. Addition of only 0.01vol% of xGnP of any size gives rise to formation of β -form of crystals. However, the peaks of the β -form disappear at higher xGnP loadings. The α -form is the most common crystal structure; the β -form of PP was found to have higher impact strength and toughness which is

attributed to the peculiar lamellar morphology of β -PP, the formation of an enlarged plastic zone and the strain induced β - α transition during mechanical deformation [24].

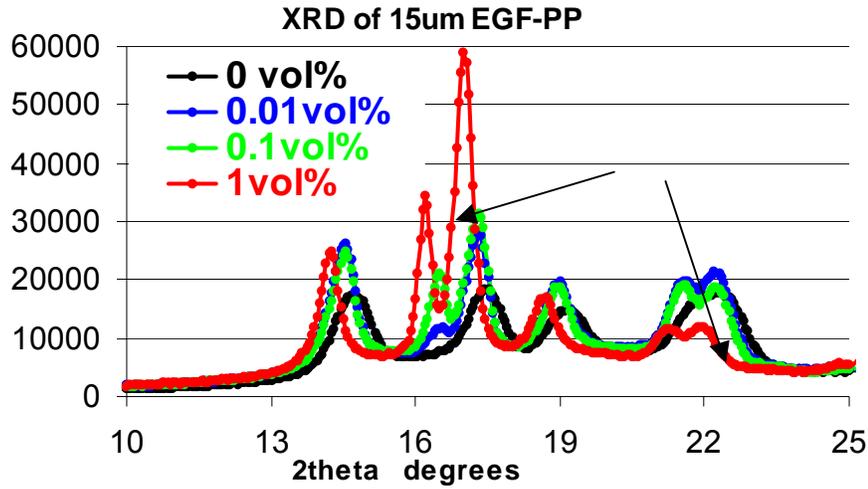


Figure 22. XRD of 15um xGnP-PP Nanocomposites

CONCLUSIONS

It is concluded that xGnP a new multifunctional nanoreinforcement developed in our lab showed higher improvement in modulus than some commercially available carbon materials at the same loading levels indicating that the exfoliated graphite has properties similar to highly crystalline graphite. The flexural strength also improved with addition of xGnP although the data point toward the need for surface treatment of the exfoliated graphite in order to improve dispersion within the polymer matrix and improve adhesion, work which is currently in progress. It was also demonstrated that xGnP increases the thermal conductivity and reduces the coefficient of thermal expansion of the neat polypropylene. The electrical conductivity and percolation threshold of carbon reinforced polypropylene nanocomposites were determined for various conductive fillers as a function of filler content, aspect ratio, geometry as well as for various fabrication methods and processing conditions. A new compounding method, the premixing of xGnP and PP in solid state and room temperature was proposed as an alternative to the solution approach that requires large amount of solvent and elevated temperature. Finally, it was found that xGnP acts as nucleating agent for polypropylene and promotes the formation of the less preferable β -phase crystals, which have better mechanical properties than the more common α -form.

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