Preparation and crystallization behaviour of PP/PP-g-MAH/Org-MMT nanocomposite

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Abstract

The melt-direct intercalation method was employed to prepare polypropylene (PP)/maleic anhydride grafted polypropylene (PP-g-MAH)/organoclay (Org-MMT) nanocomposites. X-ray diffractometer was used to investigate the intercalation effect and crystallite size in composites and TEM micrograph to observe the dispersion of Org-MMT interlayers in polypropylene. The results showed that by introducing maleated polypropylene in PP/Org-MMT composites, macromolecular segments had intercalated into interlayer space of Org-MMT. As a result, Org-MMT interlayers were dispersed evenly in polypropylene and PP/PP-g-MAH/Org-MMT nanocomposite was synthesised. The crystallite size of nanocomposite perpendicular to the crystalline plane such as (0 4 0), (1 1 0), (1 1 1), (0 4 1) is smaller than that of pristine PP, which indicated that the crystallite size of PP in nanocomposite can be diminished by adding PP-g-MAH and Org-MMT. Moreover, the non-isothermal crystallization kinetics of PP and PP/PP-g-MAH/Org-MMT nanocomposite was investigated by differential scanning calorimetry (DSC) with various cooling rates. The Avrami analysis modified by Jezioro, Ozawa method and a method developed by Liu were employed to describe the non-isothermal crystallization process of these samples. The difference in the exponent n between PP and nanocomposite, indicated that non-isothermal kinetic crystallization corresponded to tridimensional growth with heterogeneous nucleation. The values of half-time, Z, F(T) and K(T) showed that the crystallization rate of composites was faster than that of PP at a given cooling rate.

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1. Introduction

Polymer/clay nanocomposites are a class of hybrid materials composed of organic polymer matrix in which inorganic particles with nanoscale dimension are embedded [1-4]. At this scale, the inorganic fillers improve dramatically the properties of polymer even though their amount is small. These nanocomposites exhibit improved modulus, lower thermal expansion coefficient and gas permeability, higher swelling resistance and enhanced ionic conductivity compared with the pristine polymers presumably due to the nanoscale structure of the hybrids and the synergism between the polymer and the silicate [5,6]. Since a montmorillonite (one of a group of clay materials known as smectite) reinforced nylon nanocomposite with excellent mechanical properties was developed by Toyota group, much attention has been devoted to smectite as a reinforcement material for polymers [7-11]. Polypropylene (PP) is one of the most widely used polyolefinic polymers. Since it does not include any polar...
groups in its backbone, it was not thought that homogeneous dispersion of the silicate layers in PP would be realized. In general, the clay is modified with alkylammonium to facilitate its interaction with polymer matrix because the alkylammonium make the hydrophilic clay surface organophilic. Kato et al. prepared PP-based nanocomposites by melt blend of the three components (PP, PP-g-MAH and modified clay) in a twin-screw extruder [12,13]. Wolf described that the swollen organic-modified clay was compounded with PP in a twin-screw extruder at 250 °C to prepare PP/organic-modified clay nanocomposites [14]. Polypropylene is a semicrystalline polymer. The final properties of composites based on PP in an engineering application are critically dependent on the extent of crystallinity and the nature of crystalline morphology of PP, which in turn depend on the processing conditions. It is therefore necessary to understand the relationship between processing conditions and the development, nature, and degree of crystallinity of composites based on PP. In our previous studies, PP/Org-MMT nanocomposites were obtained by direct melt blend of special brand PP and Org-MMT [10,15]. In this experiment, another brand PP was used, and PIPPP-p-MAH/Org-MMT nanocomposite was synthesized successfully by melt-direct intercalation process. The crystallite size and crystal cell parameters of PIPPP-p-MAH/Org-MMT nanocomposites were investigated by X-ray diffraction analysis. Several nonisothermal crystallization kinetic equations were used to study the crystallization characteristics of PP and PIPPP-p-MAH/Org-MMT.

2. Experimental

2.1. Materials

Polypropylene (MFI is 4.0 g/10 min, density is 0.910 g/cm³, and Mw is about 60,000 g/mol) was used purchased from The Polyolefin Co., Ltd. (Singapore) and used without any treatment (the brand was FY0212). Maleated polypropylene (PP-g-MAH) with graft efficiency of 0.6 wt% was prepared by reactive extrusion in our own laboratory [9]. Na⁺-montmorillonite was available from Lia’an Chemistry Agent Factory (China), and organo-montmorillonite (Org-MMT) was synthesized in our own laboratory according to [16].

2.2. Preparation of PIPPP-p-MAH/Org-MMT nanocomposite

PP-g-MAH and Org-MMT were melt mixed in roller mill at 175-180 °C for 15 min at certain prescription to make master batch, then the master batch and conventional PP were melt mixed at certain prescription in a roller mill at 175-180 °C for 15 min. The resulting sheet was compression moulded at 180 °C for 30 min into plate with thickness of 4 mm.

2.3. Measurements

X-ray diffraction analysis (XRD) was carried out in order to confirm whether the PIPPP-p-MAH/Org-MMT nanocomposites were formed. The XRD patterns were scanned in 2θ ranges from 1.2° to 10° and at a rate of 1°/min. The interlayer distance of Org-MMT in composite was calculated from the (001) peak by using Bragg equation. Dmax-g examination was employed with Cu-Kα radiation at room temperature by using graphite-filter and it was also used to certify crystal type of PP in the nanocomposite and to investigate the change of crystallite size of PP in the composites. The diffractionograms were scanned in 2θ ranges from 2.2° to 30° and at a rate of 2°/min.

Transmission electron micrographs were obtained with TEM (100X) using an accelerating voltage of 200 kV.

A Mettler Toledo DSC-821E apparatus was used for measuring nonisothermal crystallization kinetics in the cooling mode from the molten state (melt-crystallization). The temperature and energy readings were calibrated with indium at each cooling rate employed in the measurements. All measurements were carried out in nitrogen atmosphere. For nonisothermal melt-crystallization, the raw sample was heated first to 473 K and kept for 5 min in the cell to eliminate previous thermal history. The sample was cooled at constant rates of 5, 10, 20 and 40 K/min respectively. The exothermic crystallization peak was then recorded as a function of temperature.

3. Results and discussion

3.1. X-ray diffraction analysis

The X-ray diffraction patterns of PP and PIPPP-p-MAH/Org-MMT nanocomposite are shown in Fig. 1 and X-ray parameters calculated from the (001) peaks are summarized in Table 1. As can be seen from Fig. 1 and Table 1, in the PIPPP-p-MAH/Org-MMT composites, the (001) plane peaks of Org-MMT around 2θ = 4.6°, as expected, were shifted to lower angles about 2θ = 2.3° comparable to that of Org-MMT, implying that the interlayer distance was modified from 1.9 to 3.8 Å during direct melt process. This clearly indicates that macromolecule chains had intercalated into the galleries of Org-MMT. This may be the result of the strong interaction between polar PP-g-MAH molecule and the silicate layer. PP-g-MAH can penetrate the silicate particle and intercalated into the galleries of them. As a result, PIPPP-p-MAH/Org-MMT intercalated
nanocomposite was produced. However, the result was quite different from PP/Org-MMT composite, where the (001) peak of Org-MMT did not shift. This indicated that the nonpolar macromolecular segments of PP hardly could intercalate into the interlayer of Org-MMT and that introducing PP-g-MAH is the key of preparing nanocomposite based on PP used in this experiment and Org-MMT.

3.2. Microstructure analysis

Transmission electron micrograph (TEM) was used to measure the microstructure and dispersion characterization of PP/PP-g-MAH/Org-MMT nanocomposite. Slides with a thickness around 70-80 nm have been prepared by ultramicrotomy at 16 °C and observed by TEM. Fig. 2a shown that multilayered Org-MMT interlayers with a interlayer distance of about 4 nm were observed in PP/PP-g-MAH/Org-MMT nanocomposite which gave evidence that polymer molecule had intercalated into the interlayers of Org-MMT. Fig. 2b shown that multilayered Org-MMT layers were dispersed evenly in PP matrix. It can be explained that PP-g-MAH incorporates nonpolar PP segment and polar maleic anhydride graft segment and acts as compatibility between nonpolar PP and Org-MMT.

In order to investigate the effect of PP-g-MAH and Org-MMT on the crystallization of PP, diffractograms were scanned with the range from 2.2° to 30° at the rate of 2°/min. These diffractograms were presented in Fig. 1. As shown in Fig. 1, the peak position of every crystal plane did not shift just because of addition of Org-MMT.

### Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>2θ (deg)</th>
<th>d (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>001</td>
<td>002</td>
</tr>
<tr>
<td>Org-MMT</td>
<td>4.64</td>
<td>–</td>
</tr>
<tr>
<td>PP/PP-g-MAH/Org-MMT</td>
<td>4.60</td>
<td>–</td>
</tr>
<tr>
<td>PP/PP-g-MAH/Org-MMT</td>
<td>2.30</td>
<td>4.90</td>
</tr>
</tbody>
</table>

Fig. 2. TEM micrographs of PP/PP-g-MAH/Org-MMT nanocomposite. a ×100,000; b ×20,000.
and PP-g-MAH, which indicated that crystallization type of PP did not change, still being a monoclinic crystal type. Basing on Scherrer’s equation

$$L_{\text{oa}} = \frac{K \lambda}{\beta_{\text{oa}} \cos \theta}$$  \hspace{1cm} (1)

where $L_{\text{oa}}$ is crystallite size perpendicular to reflection plane (0k1) (nm), $\beta$ is Bragg angle, $\lambda$ is wavelength of X-ray used (nm), $\beta_{\text{oa}}$ is width of diffraction beam used (rad), $K$ is shape factor of crystallite size, being related to shape of crystallite and defined as $\beta_{\text{oa}} L_{\text{oa}}$. When $\beta_{\text{oa}}$ is defined as half-bright width of diffraction peaks, $K = 0.9$. Crystallite size $L_{\text{oa}}$ of PP and composite can be calculated, and the results are summarized in Table 2.

As can be seen from Table 2, crystallite size perpendicular to the crystal plane like (040), (130), (111), (941) in composite was smaller than that of PP. This clearly indicated that crystallite size of nanocomposite decreased by introducing PP-g-MAH and Org-MMT. It can be explained that PP-g-MAH and Org-MMT acting as heterogeneous nucleating agent during crystallization of PP from melt are inclined to absorb macromolecule segments, owing to carbonyl group included in PP-g-MAH exhibits strong polarity and interlayer of Org-MMT have spacious superficial area, consequently whose movement were constrained and initiate to crystallize [10].

3.3. Crystallization behaviour of PP and PP/PP-g-MAH/Org-MMT

Moon [17] investigated glass fiber/polypropylene composite and reported that the transcrystallinity on glass fiber in PP induced the interfacial shear strength values of glass fiber/polypropylene composite to decrease. Thomason and Van Rooyen [18,19] pointed out that the transcrystallinity only appeared when the specimen was cooled down rapidly. The crystallization exotherm of PP and PP/PP-g-MAH/Org-MMT nanocomposite at various cooling rates are presented in Fig. 3. From these curves, some useful parameters, such as the peak temperature ($T_p$) and relative crystallinity ($X_r$) as a function of crystallization temperature can be obtained for describing the nontothermal crystallization behaviour of PP and PP/PP-g-MAH/Org-MMT. Firstly it is clearly seen from Fig. 3 that $T_p$ shifts, as expected, to lower temperature with increasing cooling rate for pure PP and PP/PP-g-MAH/Org-MMT. This can be explained that lower time scale will affect the polymer to crystallize as increasing cooling rate, therefore require a higher undercooling to initiate crystallization. Besides the motion of PP molecules cannot follow the cooling temperature when the specimens are cooled fast. Secondly, for a given cooling rate, $T_p$ of PP/PP-g-MAH/Org-MMT nanocomposite is higher than that of pure PP as shown in Table 4. This can be explained that carbonyl group of PP-g-MAH and particles of Org-MMT have heterogeneous nucleation effects on PP macromolecule segments. This result conforms to the conclusion we have drawn from X-ray diffraction analysis and microstructure analysis.

3.4. Nontothermal crystallization kinetics of PP and PP/PP-g-MAH/Org-MMT

The relative degree of crystallinity, $X_r$, as a function of crystallization temperature $T$ is defined as

$$X_r = \frac{\int_{T_0}^{T} \frac{dH_c}{d\theta} dT}{\int_{T_0}^{T} \frac{dH_c}{d\theta} dT} \int_{T_0}^{T_c} \frac{dH_c}{d\theta} dT$$  \hspace{1cm} (2)

where $T_0$ and $T_c$ represent the onset and end of crystallization temperatures respectively.
Fig. 4 shows the development of relative degree of crystallinity as a function of temperature for nanocomposite (PP/PP-g-MAH/Org-MMT = 68:30:2) at various cooling rates. The plots of \( X_t \) vs. \( T \) for PP is similar to that of nanocomposite (PP/PP-g-MAH/Org-MMT = 68:30:2). It can be seen that all these curves have the same sigmoidal shape, implying that only the lag effect of cooling rate on crystallization is observed. Using the following equation, \( t = (T_0 - T) / \phi \) (\( T \) is the temperature at crystallization time \( t \), and \( \phi \) is the cooling rate), the horizontal temperature axis in Fig. 4 could be transferred into a time scale (Fig. 5). It shows that the higher the cooling rate, the shorter the time for completing crystallization is. The halftime of nonisothermal crystallization \( t_{1/2} \) could be obtained from Fig. 5 for PP and PP/PP-g-MAH/Org-MMT, and the results are listed in Table 3. It shows that, as expected, the value of \( t_{1/2} \) decreases with increase of cooling rates for PP and PP/PP-g-MAH/Org-MMT. Moreover, at a given cooling rate, the values of \( t_{1/2} \) for PP/PP-g-MAH/Org-MMT are smaller than that of PP, signifying that the addition of PP-g-MAH and Org-MMT can accelerate the overall crystallization process.

Table 3
Nonisothermal crystallization kinetic parameters for PP and PP/PP-g-MAH/Org-MMT nanocomposite

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \phi ) (K/min)</th>
<th>( k )</th>
<th>( t_{1/2} ) (min)</th>
<th>( T_g ) (K)</th>
<th>( \Delta H ) (J/g)</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>5</td>
<td>4.13</td>
<td>0.42</td>
<td>2.62</td>
<td>315.7</td>
<td>100.60</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4.12</td>
<td>0.85</td>
<td>1.36</td>
<td>382.2</td>
<td>97.34</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>3.72</td>
<td>1.03</td>
<td>0.78</td>
<td>377.3</td>
<td>96.77</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>3.71</td>
<td>1.04</td>
<td>0.98</td>
<td>371.4</td>
<td>100.97</td>
</tr>
<tr>
<td>PP/PP-g-MAH/Org-MMT</td>
<td>5</td>
<td>3.37</td>
<td>0.55</td>
<td>1.61</td>
<td>391.8</td>
<td>98.29</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3.17</td>
<td>0.94</td>
<td>0.93</td>
<td>387.2</td>
<td>91.32</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>2.85</td>
<td>1.04</td>
<td>0.53</td>
<td>333.5</td>
<td>85.85</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>2.77</td>
<td>2.04</td>
<td>0.33</td>
<td>378.9</td>
<td>97.42</td>
</tr>
</tbody>
</table>

Assuming that nonisothermal crystallization process may be composed of infinitesimally small isothermal crystallization steps, Ozawa [28] extended the Avrami equation to the nonisothermal case as following:

\[
1 - X_t = \exp\left( -K(T) / \phi \right)
\]

(3)

where \( K(T) \) is the function of cooling rate, \( \phi \) the cooling rate and \( m \) is the Ozawa exponent depending on the dimension of the crystal growth. Taking double-logarithmic form:

\[
\ln(-\ln(1 - X_t)) = \ln K(T) - m \ln \phi
\]

plotting \( -\ln(1 - X_t) \) against \( -\ln \phi \) at a given temperature, a straight line would be obtained if the Ozawa method is valid. Thus \( K(T) \) and \( m \) can be estimated from the intercept and slope respectively. The results based on Ozawa method are shown in Fig. 6 and Table 4. It was clearly seen that the curves in the plots of \( -\ln(1 - X_t) \) vs. \( -\ln \phi \) for PP and PP/PP-g-MAH/Org-MMT exhibit better linear relationship. The value of \( K(T) \) for both PP and PP/PP-g-MAH/Org-MMT increased with the decrease of crystallization temperature, but the value of \( K(T) \) for PP/PP-g-MAH/Org-MMT was larger than that of PP at a given crystallization temperature.
implying that PP/PP-g-MAH/Org-MMT crystallized at a quicker speed than PP. The value of exponent $m$ varied from 1.96 to 2.09 for PP and from 1.24 to 2.6 for PP/PP-g-MAH/Org-MMT. It is interesting to note that the value of exponent $m$ for PP/PP-g-MAH/Org-MMT is scattered and decreased with the decrease of crystallization temperature, which indicates that the nonisothermal crystallization behaviour of PP/PP-g-MAH/Org-MMT is more complex than that of PP.

The alternative approach adopted here was Avrami equation [21],

$$1 - X_t = \exp(-Z_{t}^{n})$$

where the exponent $n$ is a mechanism constant depending on the type of nucleation and growth process parameters, and $Z_t$ is a composite rate constant involving both nucleation and growth rate parameters. Using Eq. (5) in double-logarithmic form,

$$\ln(-\ln(1-X_t)) = \ln Z_t + n \ln t$$

plotting $\ln(-\ln(1-X_t))$ against $\ln t$ for each cooling rate, a straight line is obtained with the data at low degree of crystallinity in the linear regression only (see Fig. 7), thus two adjustable parameters, $Z_t$ and $n$, can be estimated. It should be taken into account that in nonisothermal crystallization $Z_t$ and $n$ do not have the same physical significance as in the isothermal crystallization due to the fact that under nonisothermal crystallization the temperature changes constantly. This affects the
rates of both nuclei formation and spherulite growth since they are temperature dependent. In this case, \( Z \) and \( n \) are two adjustable parameters only to be fitted to the data. Although the physical meaning of \( Z \) and \( n \) cannot be related in a simple way to the nonisothermal case, the equation (5) can still provide further insight into the kinetics of nonisothermal crystallization.

Considering the nonisothermal character of the process investigated, the final form of the parameter characterizing the kinetics of nonisothermal crystallization was given by Jezernik [22]:

\[
\ln Z = \ln Z_e + \frac{\ln \phi}{\phi} \tag{7}
\]

The results obtained from Avrami plots and Jezernik method are listed in Table 5. The exponent \( n \) of PP varied from 3.71 to 4.13, from 2.77 to 3.37 for PP/PP-g-MAH/Org-MMT. Although the exponent \( n \) in nonisothermal crystallization displayed a wide range of values and was more scattered than those obtained from isothermal crystallization [23], it is interesting that the exponent \( n \) for PP was larger than that for PP/PP-g-MAH/Org-MMT at every cooling rate, showing that the PP-g-MAH and Org-MMT acted as a nucleating agent in PP matrix, indicating that nonisothermal crystallization of PP/PP-g-MAH/Org-MMT corresponds to multidimensional growth with heterogeneous nucleation, different from that of PP. For both PP and PP/PP-g-MAH/Org-MMT, as expected, the value of \( Z_e \) increases with increase of cooling rates. The value of \( Z_e \) for PP/PP-g-MAH/Org-MMT is larger than that for PP at a given cooling rate, implying that PP/PP-g-MAH/Org-MMT finished crystallization process at quicker speed than PP. A method developed by Liu [24] was employed to describe the nonisothermal crystallization in order to make comparison. For the nonisothermal crystallization process, physical variables relating to the process are relative degree of crystallinity \( \chi \), cooling rate \( \dot{\phi} \), and crystallization temperature \( T \). Both Ozawa and Avrami equations give their relationship as following:

\[
\ln Z_e + n \ln \phi = \ln K(T) - a \ln \dot{\phi} \tag{8}
\]

by rearrangement at a given crystallinity \( \chi \).

\[
\ln \phi = \ln \phi(T) - a \ln \dot{\phi} \tag{9}
\]

where \( F(\dot{T}) = [K(T)/Z_e]^{1/\phi} \) refers to the value of cooling rate, which must be chosen within unit crystallisation time when the measured system amounts to a certain degree of crystallinity, \( a = n/m \), the ratio of Avrami exponent \( n \) to Ozawa exponent \( m \). According to Eq. (9), at a given degree of crystallinity, plotting \( \ln \phi \) vs. \( \ln \dot{\phi} \) (Fig. 8) yields a linear relationship between \( \ln \phi \) and \( \ln \dot{\phi} \). The kinetic parameter \( F(\dot{T}) \) and \( a \) are determined from the intercept and slope of the lines. They are listed in Table 5 for PP and PP/PP-g-MAH/Org-MMT. It can be seen from Table 5 that the value of \( a \) for PP varies from 1.33 to 1.38, from 1.24 to 1.37 for PP/PP-g-MAH/Org-MMT, and that the value of \( F(\dot{T}) \) systematically increases with increase of relative degree of crystallinity. It is also obvious that for a certain relative degree of crystallinity, the value of \( F(\dot{T}) \) for PP/PP-g-MAH/Org-MMT is smaller than that for PP; that is, amounting to same relative degree of crystallinity, PP/PP-g-MAH/Org-MMT requires smaller cooling rate, which indicate

![Fig. 8. Plots of ln \( \phi \) vs. ln \( \dot{\phi} \) for nanocomposite during nonisothermal crystallization process PP/PP-g-MAH/Org-MMT = 0.6:30:2.](image_url)

Table 5
Nonisothermal crystallization kinetic parameters for PP and PP/PP-g-MAH/Org-MMT nanocomposite at different relative degree of crystallinity

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \chi )</th>
<th>( \phi )</th>
<th>( F(\dot{T}) )</th>
<th>( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
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<td>0.9946</td>
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<td>0.4</td>
<td>1.33</td>
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<td></td>
<td>0.6</td>
<td>1.34</td>
<td>18.17</td>
<td>0.9948</td>
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<td></td>
<td>0.8</td>
<td>1.38</td>
<td>21.98</td>
<td>0.9949</td>
</tr>
<tr>
<td>PP/PP-g-MAH/Org-MMT</td>
<td>0.2</td>
<td>1.24</td>
<td>5.83</td>
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</tr>
<tr>
<td></td>
<td>0.4</td>
<td>1.29</td>
<td>8.00</td>
<td>0.9985</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>1.30</td>
<td>10.28</td>
<td>0.9994</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>1.37</td>
<td>13.67</td>
<td>0.9992</td>
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</table>
that PP/PP-g-MAH/Org-MMT crystallizes at a quicker rate than PP. The conclusion agrees with the one drawn from Avrami analysis and Ozawa analysis. Obviously this approach is successful in describing the nonisothermal process of PP and PP/PP-g-MAH/Org-MMT as PEEK [24], PHB-PVAc blends [25] and POM/Org-MMT nanocomposite [9].

4. Conclusion

As nonpolar PP macromolecule could hardly intercalate between the interlayers of Org-MMT, introducing PP-g-MAH is necessary for preparing PP/PP-g-MAH/Org-MMT nanocomposite. The crystallite size perpendicular to the crystalline plane like (0 4 0), (1 3 0), (1 1 1), (0 4 1) of PP/PP-g-MAH/Org-MMT nanocomposite is smaller than that of pristine PP. This clearly indicated that Org-MMT and PP-g-MAH have heterogeneous nucleation effect on pure PP, which results in a decrease of crystallite size. Study on nonisothermal crystallization kinetics shows: The Ozawa analysis can be used to describe the nonisothermal crystallization of PP and PP/PP-g-MAH/Org-MMT, but the value of n is scattered for PP/PP-g-MAH/Org-MMT. The Avrami analysis modified by Jenomy and a method developed by Mo were successful in describing the nonisothermal crystallization process of PP and PP/PP-g-MAH/Org-MMT. The difference in the exponent n between PP and PP/PP-g-MAH/Org-MMT, indicated that nonisothermal kinetic crystallization (for PP/PP-g-MAH/Org-MMT) corresponded to twodimensional growth with heterogeneous nucleation. The half-time $t_{1/2}$, $X_c$, $F(T)$ and $K(T)$ showed that the crystallization rate of PP and composites increased with increasing of cooling rates, and that the crystallization rate of composite was faster than that of PP at a given cooling rate.

References