Dynamic Crystallization Kinetics and Nucleation Parameters of New Generation of Nanocomposites based on Isotactic polypropylene and MoS₂ Inorganic Nanotubes

Mohammed Naffakh,^{1,*} Maja Remškar,^{2,3} Carlos Marco,¹ Marián A. Gómez-Fatou¹

¹ Departamento de Física e Ingeniería de Polímeros, Instituto de Ciencia y Tecnología de Polímeros, CSIC, c/ Juan de la Cierva, 3, 28006, Madrid, Spain.

² Jožef Stefan Institute, Jamona 39, SI-1000 Ljubljana, Slovenia

³ Centre of Excellence PoliMat, Tehnoloski Park 24, SI-1000 Ljubljana, Slovenia

Abstract. Differential scanning calorimetry (DSC) and time-resolved synchrotron X-ray diffraction have been used to investigate the dynamic crystallization behaviour and crystalline structure of novel nanocomposites based on isotactic polypropylene (iPP) and molybdenum disulfide inorganic nanotubes (INT-MoS₂). The influence of the INT-MoS₂ content and different cooling rates on the crystallization behaviour have been studied. The crystallization exothermic peak shifted to higher temperature, and the overall crystallization time was reduced by increasing the INT-MoS₂. The dynamic crystallization kinetics was analyzed using the Ozawa-Avrami method, which was successful in describing the dynamic crystallization behaviour of these new nanocomposites. On the other hand, study of the nucleation activity using Dobrev method revealed that the INT-MoS₂ had an efficient nucleation effect on the monoclinic crystal-form of iPP. Moreover, this effect was corroborated by the results of the crystallization activation energy, calculated using Kissinger and Takhor methods, which also confirmed the fact that the addition of INT-MoS₂ made the molecular chains easier to crystallize, and increased the crystallization rate of iPP.

* To whom correspondence should be addressed. E-mail: mnaffakh@ictp.csic.es

1. Introduction

The discovery of carbon fullerenes by Kroto, Smalley and Curl [1] in 1985 and later of carbon nanotubes by Iijima in 1991 [2] served as a turning point in the exploration of the potential of these nanostructures.. The development of these nanostructures is not limited to carbon and it was soon recognized that layered metal dichalcogenides such as WS₂ and MoS₂ could also form these genuine property. The first synthesis of such nanophases was reported by Tenne in 1992 and 1993, respectively [3, 4], leading to the birth of a new field of inorganic chemistry, that is, one dealing with polyhedral (closed hollow) nanostructures. Since then, the number of articles related with the successful growth of inorganic nanotubes (INT) and fullerene-like (IF) nanoparticles from inorganic compounds with layered two-dimensional structures has increased rapidly, showing the importance of this field for nanotechnology [5, 6]. Various potential applications have been proposed for these nanophases due to their excellent solid lubrication behaviour, suggesting many applications in, for example, the automotive and aerospace industries, home appliances, and recently for medical technology [6]. In particular, the revolutionary properties of inorganic fullerene-like nanoparticles (e.g. tungsten disulfide, IF-WS₂), such as high modulus and low friction coefficient, attributed to their small size, closed structure and chemical inertness, make them potential candidates to improve the thermal, mechanical and tribological properties of thermoplastic polymers, as has been shown for isotactic polypropylene (iPP) [7, 8], polyphenylene sulfide (PPS) [9-11] and PEEK [12] produced via melt blending, without using modifiers or surfactants. Other potential applications, in catalysis, rechargeable batteries, drug delivery, solar cells and electronics have also been reported [6]. The most relevant developments in this field over the last years as well as long-term potential applications of inorganic fullerene-like nanoparticles and inorganic nanotubes have been presented in a reviewed by Tenne [13].

The unidirectional growth of materials to form nanowires or nanotubes has attracted enormous interest in recent years. Due to their many interesting properties (i.e. small dimensions, high anisotropy, and intriguing tube-like structures) carbon nanotubes (CNT) were found to be promising additives to polymeric materials leading to the enhancement of various properties of the resulting composites [14-16]. However, the fabrication of high quality composites often requires very pure starting material, good particle dispersion and strong interaction and adhesion between nanoparticles and polymer matrix. These requirements still pose great difficulties for CNT composites. For these reasons synthesis of alternative filler particle types, in particular inorganic nanotubes, becomes increasingly important. Recently, INT like-WS₂ are routinely synthesized in large amounts by ApNano Materials, Inc. (NanoMaterials, Ltd.) (<http://www.apnano.com>) [17]. The nanotubes are relatively long with respect to their diameter and it is this high aspect ratio property that gives them their unique strength and chemical properties. The process does not require a catalyst, and the precursors (tungsten oxide and H₂S or sulfur) are relatively inexpensive. Therefore, the moderate cost of such nanotubes may afford numerous applications in the field of polymer nanocomposites.

In this context, in our previous investigation [18] we have successfully developed a new family of nanocomposites which integrated promising molybdenum disulfide nanotubes (MoS₂) in isotactic polypropylene (i.e. the most widely investigated polymer for use in the preparation and application of nanocomposites) by means of the most simple, cost-effective and ecologically friendly processing way (i.e. melt-processing route). The successful dispersion of INT-MoS₂ induced a remarkable improvement in the thermal and mechanical properties of iPP, without using modifiers or surfactants. The present work is particularly focused on the analysis of the dynamic crystallization behaviour of these nanocomposites to better understand the influence of INT-MoS₂ on the crystallization. It is well known that the

properties of a crystalline polymer including the thermodynamic, physical or mechanical ones depend on the details of the structure and morphology that evolve from the melt. Thus, detailed investigation of the influence of INT-MoS₂ on the crystallization kinetics of iPP would give an insight into the structure–property–performance relationship of such nanocomposites

2. Experimental section

2.1. Materials and processing. The polypropylene (PP) used as matrix was an isotactic homopolymer, provided by REPSOL, with a polydispersity of 4.77, an isotacticity of 95% and a viscosity average molecular weight of 179,000 g/mol. The INT-MoS₂ were provided by NANOTUL (Slovenia) and have been synthesized using Mo₆S₂I₈ nanowires as precursor crystals by sulphurization [19] at 1073 K [20]. X-ray fluorescence analysis revealed MoS₂ (99.9 %) with some traces of the remained iodine (200 ppm). Several concentrations of INT-MoS₂ (0.1, 0.5 and 1 wt. %) were introduced in the iPP matrix by melt-mixing using a micro-extruder (Thermo-Haake Minilab system) operated at 210 °C and a rotor speed of 150 rpm for 15 min.

2.2. Characterization techniques. The crystallization behaviour of the iPP/INT-MoS₂ nanocomposites were investigated by DSC using a Perkin Elmer DSC7/Pyris differential scanning calorimeter, calibrated with indium ($T_m = 156.6$ °C, $\Delta H_m = 28.45$ kJ/kg) and zinc ($T_m = 419.47$ °C, $\Delta H_m = 108.37$ kJ/kg). The experiments were carried out in a nitrogen atmosphere at a rate flow of 25 ml/min, using approximately 10 mg of sample sealed in aluminium pans. Before collecting the data of crystallization, the samples were heated to 210°C and held in the molten state for 5 min to eliminate the influence of thermal history. Then, the crystallization of the samples under dynamic conditions was carried out by cooling from 210°C to 30°C at 1, 2, 5, 10 and 20°C/min. Partial areas, corresponding to a given percentage of the total transformation, were determined from the data points of the exotherm. For the estimation of

the crystallinity of the samples, a value of 190 J/g for the melting enthalpy of 100% crystalline iPP was used [21].

Small and Wide-angle X-ray scattering (SAXS/WAXS) experiments using synchrotron radiation were performed at the A2 beamline of the HASYLAB synchrotron facility (DESY, Hamburg). The experiments were performed with monochromatic X-rays of 0.15 nm wavelength using a germanium single crystal as the dispersing element. The scattering was detected with a linear Gabriel detector. The sample to detector distance of SAXS was 2360 mm, and for WAXS was 135 mm. The scattering angle of the SAXS pattern was calibrated with the RTT (rat tail tendon), and that of the WAXS profile was calibrated with a PET standard. The maximum of the Lorentz-corrected SAXS diffractograms was used to calculate the long period ($L=1/s_{\max}$) as a function of the temperature. L represents the sum of the average thickness of the crystal lamellae and of the interlamellar amorphous regions. The methodology used in the dynamic crystallization experiments of the iPP/INT-MoS₂ nanocomposites by SAXS/WAXS was similar to that described for the calorimetric experiments. Measurements were performed with acquisition time of 12 s (wait time = 2 s and read time = 10 s).

3. Results and discussion

The crystallization rate of polymers is a very important property from an industrial point of view, as it affects the production time of thermoplastic goods. Crystallization is considered to occur in two steps, which is usually preceded by homogeneous nucleation, heterogeneous nucleation, or self-nucleation and then by growth of the crystal with crystallization time. For a crystallizable polymer, nucleation may be caused by homogeneous or by heterogeneous (impurities, nucleating agent, or others), which can control the structure and physical properties of polymer. Therefore, overall crystallization behaviour of polymers can be analyzed by the observation of the rates of nucleation and growth or the overall rate of

crystallization of polymers which can forecast relationship between the structures and preparation conditions of the polymers.

It is well known that the crystallization of polymers releases a significant amount of heat that makes DSC a preferred method for measuring the overall crystallization kinetics. The measured rate of heat release is assumed to be proportional to the macroscopic rate of crystallization:

$$\frac{dQ}{dt} = Q_c \frac{dx}{dt} \quad (1)$$

where Q_c is the measured heat of crystallization. The value of Q_c is calculated by integration of a DSC peak. The values of Q_c can further be used to determine the crystallization rate, dx/dt , as well as the extent of the melt conversion:

$$x(t) = \frac{1}{Q_c} \int_0^t \frac{dQ}{dt} dt \quad (2)$$

The value of $x(t)$ varies from 0 to 1 and represents the degree of conversion. The transformation from temperature to time is performed using a constant cooling rate ϕ :

$$t = \frac{T_0 - T}{\phi} \quad (3)$$

where T is the temperature at time t and T_i is the temperature at the beginning of crystallization. Figure 1 shows the typical dynamic crystallization thermograms obtained at various cooling rates for neat iPP and the iPP/INT-MoS₂ nanocomposite with an INT-MoS₂ content of 1wt. %. In both cases, the peak temperature (T_p), which corresponds to the maximum crystallization rate, shifts to lower temperature with increasing cooling rate. It is also seen the lower the cooling rate, the earlier the crystallization starts. On the other hand, Figure 2 presents the crystallization fraction or conversion as function of temperature. According to Eq. 3, the value to T on X-axis in Figure 2 can be transformed into crystallization time as shown in Figure 3. The lower the cooling rate, the larger temperature (time) range at which the crystallization occurs, which indicates that the transformation is

controlled by nucleation. In addition, all curves have the same S (or reversed S) shape, indicating that only the retardation effect of cooling rate on the crystallization is observed in these curves. However, the most obvious result was the influence of INT-MoS₂ on, for example, the crystallization temperature (T_p) of iPP for a particular cooling rate. The crystallization temperature of iPP increases with the incorporation of INT-MoS₂ at all cooling rates as shown in Figure 4. This effect was clearly observed to be a function of composition, manifesting a significant increase of around 4 °C of this parameter at a cooling rate of 10°C/min. At higher INT-MoS₂ concentrations the value of T_p for iPP continues to rise and tends to stabilize for the highest concentrations of 0.5 y 1 %, where increments of around 10°C in the value of T_p were registered. In the same way, the crystallinity increases up to 14 % with the IF-MoS₂ content, from a average value of 50 % for iPP, to values of 54, 57 and 56 % for the nanocomposites with 0.1 wt.%, 0.5 wt.% and 1 wt.%, respectively. The increase in the crystallization temperature and crystallinity of iPP with increasing INT-MoS₂ content, suggests that INT-MoS₂ can effectively act as nucleating agent in iPP/INT-MoS₂ nanocomposites. It is generally accepted that the addition of nanoparticles into the polymer matrix favors heterogeneous nucleation and thus is expected to make the molecular chains of polymer matrix easier to crystallize and increased the crystallization rate of composites in contrast to that of neat polymer (e.g. increase of peak crystallization temperature of polymer matrix). Such a result has already been found with other nanocomposite systems, such as nylon-6/clay [22], PEN/Silica [23], PEN/MWCNT [24], iPP/SiO₂ [25], iPP/IF-WS₂ [7], nylon-6/SWNT [26], iPP/MCWNT [27] and iPP/C₃N₄ [28]. However, in some specific systems, we have observed that the incorporation of IF-WS₂ or modified SWCNTs induces a variation of the crystallization behaviour of polymeric materials like PEEK or PPS with increasing nanofiller content (i.e a drastic change from promotion to retardation and vice-versa [10, 12, 29]).

In order to quantitatively describe the evolution of crystallinity during dynamic crystallization a number of models have been proposed in the literature. In this investigation, the Lui method was tested.

3.3. Combined Ozawa-Avrami approach. A convenient approach adopted here for describing non-isothermal crystallization was the Liu model [30]. By combining the Avrami [31] and Ozawa [32] equations, a new treatment was proposed and proved to be suitable and convenient to handle the non-isothermal crystallization of poly(aryl ether ether ketone ketone) (PEEKK) as well as in other recently reported studies on PPS/IF-WS₂ [10, 11] and iPP/C₃N₄ [28]. As the degree of conversion (x) was related to the cooling rate ϕ and the crystallization time t (or temperature T), the relation between ϕ and t could be defined for a given degree of conversion. Consequently, a new kinetic equation for dynamic crystallization was derived:

$$\ln \phi = \ln f(T) - \alpha \ln t \quad (4)$$

where $f(T) = [k'(T)/k]^{1/m}$, refers to the value of cooling rate chosen at unit crystallization time, when the system has a certain degree of crystallinity, α is the ratio of the Avrami exponents to Ozawa exponents (i.e. $\alpha = n/m$). According to Eq. 4, at a given degree of conversion, the plot of $\ln \phi$ vs. $\ln t$ gives a series of lines as can be seen in Figure 5. The good linearity of the plots verifies the advantage of the combined approach applied in this case. The values of $f(T)$ and α are listed in Table 1, from which one can read that the values of $f(T)$ increase systematically with increasing relative crystallinity, indicating that at unit crystallization time, a higher cooling rate should be required in order to obtain a higher degree of crystallinity, whilst, the values of the parameter α are almost constant (eg. $\alpha_{iPP} = 1.35-1.50$ and $\alpha_{I_{wt.\%} INT-MoS_2} = 1.12-1.15$). However, the most important observation was the influence of INT-MoS₂ concentration on the value of $f(T)$ of iPP for a particular degree of conversion. The value of $f(T)$ for neat iPP is higher than that for nanocomposites, which implies that the composites

require a lower heating rate to approach an identical degree of crystalline transformation. In other words, the crystallization rate of the nanocomposites is lower than that of neat iPP. This result suggests that the presence of INT-MoS₂ acts as nucleating sites for the dynamic crystallization process of iPP [23].

3.4. Nucleation ability. Dobрева and Gutzow [33, 34] developed a simple method for calculating the nucleation activity of foreign substrates in polymer melt. Nucleation activity (ϕ) is a factor by which the work of three-dimensional nucleation decreases with the addition of a foreign substrate. If the foreign substrate is extremely active, ϕ approaches 0, while for inert particles, ϕ approaches 1. For homogeneous nucleation from a melt near the melting temperature, the cooling rates can be written as:

$$\ln \phi = A - \frac{B}{\Delta T_p^2} \quad (5)$$

while for the heterogeneous case,

$$\ln \phi = A - \frac{B^*}{\Delta T_p^2} \quad (6)$$

$$\phi = \frac{B^*}{B} \quad (7)$$

where ϕ is the cooling rate, A is a constant, and ΔT_p is the degree of supercooling, i.e. $\Delta T_p = T_m - T_p$, and T_p is the temperature corresponding to the peak temperature of the DSC crystallization curves. B is a parameter that can be calculated from the following equation:

$$B = \frac{\omega \sigma^3 V_m^2}{3n k_B T_m^0 \Delta S_m^2} \quad (8)$$

where ω is a geometrical factor; σ is the specific energy, V_m is the molar volume of the crystallizing substance, n is the Avrami exponent, ΔS_m is the entropy of melting, k_B is the Boltzman constant and T_m^0 is the infinite crystal melting temperature. In Figure 6, eqs. 5 and 6 are represented for neat iPP and its nanocomposites, considering a value of 196 °C for the thermodynamic equilibrium melting temperature of iPP [8]. From the slopes of the linear

plots, the values of B and B^* can be calculated for iPP and the nanocomposites, respectively, and the results of all iPP/INT-MoS₂ nanocomposites are listed in Table 1. As can be seen, the addition of INT-MoS₂ cause a reduction of ϕ which reaches a value of 0.69 for a concentration of 1 wt.% of INT-MoS₂, indicating that INT-MoS₂ was acting effectively as a nucleating agent in the iPP matrix. The higher value of INT-MoS₂ obtained at 1wt.% is above the values reported in the literature for other fillers including nanometric silica particles (e.g. 0.94 [25]) and carbon nitrides C₃N₄ (e.g. 0.82 [28]) and is comparable to MWCNTs [27].

3.5. Effective energy barrier. Crystallization activation energy, or effective energy barrier ΔE , can be used to estimate the growth ability of the chain segments. Considering the variation of the peak temperature T_p with the cooling rate ϕ , ΔE could be determined as following:

1. Kissinger model [35]

$$\ln\left(\frac{\phi}{T_p^2}\right) = \text{Cons} \tan t - \frac{\Delta E}{RT_p} \quad (9)$$

2. Takhor model [36]

$$\ln(\phi) = \text{Cosn} \tan t - \frac{\Delta E}{RT_p} \quad (10)$$

where R is the universal gas constant. Figure 7 shows an example of the plots of Kissinger and Takhor models. Linearity of these plots was the most popular testing methods for the validity of the calculations of the effective energy barrier and the results of all iPP/INT-MoS₂ nanocomposites are listed in Table 1. As can be seen, the isokinetic models of Kissinger and Takhor based on one experimental point from each curve (the maximum of the crystallization peak) all showed that the nanocomposites had lower values of ΔE that of iPP. The addition of INT-MoS₂ caused a decrease in the ΔE which made the molecular chains of iPP easier to crystallize, and increased the crystallization rates due to the nucleation activity of the INT-MoS₂.

3.6. Crystal morphology and structure. Understanding the structure of new polymer nanocomposites requires advanced experimental techniques. As an example, electromagnetic radiation can be used to obtain information about materials whose dimensions are on the same order of magnitude as the radiation wavelength. Scattering of X-rays is caused by differences in electron density. Since the larger the diffraction angle the smaller the length scale probed, wide angle X-ray diffraction (WAXD) is used to determine the crystal structure on the atomic length scale while small-angle X-ray scattering (SAXS) is used to explore the microstructure at the nanometer scale. Figure 8 shows the in-situ WAXS experiments of an iPP nanocomposite containing 1 wt.% of INT-MoS₂ using synchrotron radiation. Under the dynamic crystallization conditions, iPP crystallized in the α , or monoclinic form. The WAXS diffractograms of iPP/INT-MoS₂ nanocomposites only present reflections associated to the crystalline planes characteristic of the monoclinic polymorph of iPP [7]. No other crystalline forms of iPP were detected during cooling of the nanocomposites. On the other hand, the dependence of the lamellar structure of iPP on composition can also be obtained from the SAXS experiments of the nanocomposites during the crystallization from the melt at 10 °C/min. As an example, the results obtained at room temperature indicated that the addition of INT-MoS₂ caused no appreciable change in the long period (L) of iPP (i.e. ~ 15 nm). From the results of the L data, the possible role of the INT-MoS₂ on the variation of thickness of the crystal lamellae of iPP can be investigated. As noted previously, L can be considered as the sum of the average thickness of the crystal lamellae and of the interlamellar amorphous regions. In addition, the parameter L and the crystallinity can also be used as a simple approximation to calculate the average thickness of the crystal lamellae of iPP. Therefore, the increase in crystallinity of the composites, observed from the DSC data during the dynamic crystallization, could be connected to the increase of the size of the crystallites of iPP in the iPP/INT-MoS₂ nanocomposites.

Conclusion

On the basis of the experimental and theoretical analyses, the study of the dynamic crystallization kinetics of iPP/INT-MoS₂ nanocomposites provides a picture describing the transformation of iPP molecules from the non-ordered state to the ordered state. The analysis of the influence of INT-MoS₂ on the dynamic crystallization kinetics of iPP shows a significant dependence on INT-MoS₂ content and cooling rate. The crystallization temperature for the iPP/INT-MoS₂ nanocomposites decreased with increasing cooling rate for a given INT-MoS₂ content and increased with INT-MoS₂ content for a given cooling rate. The incorporation of INT-MoS₂ induces an increase in the crystallinity, whilst maintaining the monoclinic crystalline structure of iPP. On the other hand, the method developed by Liu et al., which combines the theories of Avrami and Ozawa, was successful in describing the crystallization of iPP/INT-MoS₂ nanocomposites. The parameter $f(T)$, which has physical and practical significance, increased with INT-MoS₂, indicating that the crystallization rate increased with the INT-MoS₂ content compared to iPP. Therefore, INT-MoS₂ acted as nucleation agents in the iPP matrix, and the nucleating activities, which indicated the contribution of the nanofiller to the polymer matrix, revealed that INT-MoS₂ has a remarkable nucleation effect on iPP. Finally, the energy barrier governing the dynamic crystallization based on Kissinger and Takhor models, all showed iPP/INT-MoS₂ nanocomposite had lower value of ΔE than of neat iPP, which indicated the nanocomposite has a faster crystallization rate.

Acknowledgements

Dr. M. Naffakh would like to express his sincere thanks to the Consejo Superior de Investigaciones Científicas (CSIC) for postdoctoral contract (I3PDR-6-02), financed by the European Social Fund, the European Commission for the X-ray synchrotron experiments performed at the Soft Condensed Matter A2 beamline at HASYLAB (DESY-Hamburg, I-

20100101 EC). Prof. M. Remskar would like to thank Janez Jelenc for help in synthesis of MoS₂ nanotubes. Work was partially financed by Ministry of Higher Education, Science and Technology of the Republic of Slovenia and by the FOREMOST project of the European Union 6-th Framework Program under contract NMP3-CT-2005-515840.

References

- (1) Kroto, H. W.; Heath, J. R.; O'Brien, S. C.; Curl, R. F.; Smalley, R. E. *Nature* **1985**, 318, 162–163.
- (2) Iijima, S. *Nature* **1991**, 354, 56–58.
- (3) Tenne, R.; Margulis, L.; Genut, M.; Hodes, G. *Nature* **1992**, 360, 444–445.
- (4) Margulis, L.; Salitra, G.; Tenne, R.; Talianker M. *Nature* **1993**, 365, 113–14.
- (5) Remškar, M. *Adv. Mater.* 2004, 16, 1497–1502.
- (6) Tenne, R. *Nat. Nanotechnol.* **2006**, 1, 103–111.
- (7) Naffakh, M.; Martín, Z.; Fanegas, N.; Marco, C.; Gómez, M. A.; Jiménez, I. *J. Polym. Sci. Part B: Polym. Phys.* **2007**, 45, 2309–2321.
- (8) Naffakh, M.; Martín, Z.; Marco, C.; Gómez, M. A.; Jiménez, I. *Thermochim. Acta* **2008**, 472, 11–16.
- (9) Naffakh, M.; Marco, C.; Gómez, M. A.; Jiménez, I. *J. Phys. Chem. B* **2008**, 112, 14819–14828.
- (10) Naffakh, M.; Marco, C.; Gómez, M. A. J.; Jiménez, I. *J. Phys. Chem. B* **2009**, 113, 7107–7115.
- (11) Naffakh, M.; Marco, C.; Gómez, M. A.; Gómez-Herrero, J.; Jiménez, I. *J. Phys. Chem. B* **2009**, 113, 10104–10111.
- (12) Naffakh, M.; Diez-Pascual, A.M.; Marco, C.; Gómez, M. A.; Jiménez, I. *J. Phys. Chem. B* **2010**, 114, 11444–11453.

- (13) Tenne, R.; Redlich, M. *Chem. Soc. Rev.* **2010**, 39, 1423–1434.
- (14) Moniruzzaman, M.; Winey, K. I. *Macromolecules* **2006**, 39, 5194-5205.
- (15) Maser, W. K.; Benito, A. M.; Castel, P.; Sainz, R.; Martínez, M. T.; Naffakh, M.; Marco, C.; Ellis, G.; Gómez, M. A. In *Nanostructured Materials for Advanced Technological Applications*; Reithmaier, J. P.; Petkov, P.; Kulisch, W.; Popov, C.; Eds.; NATO Science for Peace and Security Series – B: Physics and Biophysics, 2009; p181.
- (16) Bose, S.; Khare, R. A.; Moldenaers, P. *Polymer*, **2010**, 51, 975-993.
- (17) Zak, A.; Sallacan-Ecker, L.; Margolin, A.; Genut, M.; Tenne, R. *Nano* **2009**, 4(2), 91-98.
- (18) Naffakh, M.; Remškar, M.; Marco, C.; Gómez, M. A.; Jiménez, I. Submitted (2010).
- (19) Remskar, M.; Mrzel, A.; Virsek, M.; Jesih, A. *Adv. Mater.* **2007**, 19, 4276.
- (20) Remskar, M.; Virsek, M.; Mrzel, A. *Apply. Phys. Lett.* **2009**, 95, 133122.
- (21) Li, J. X.; Cheung, W. L.; Demin, J. *Polymer* **1999**, 40, 1219-1222.
- (22) Devaux, E.; Bourbigot, S.; El Achari, A. *J. Appl. Polym. Sci.* **2002**, 86, 2416-23.
- (23) Kim, S. H.; Ahn, S. H.; Hirai, T. *Polymer* 2003, 44, 5625-34.
- (24) Kim, J. Y.; Park, H. S.; Kim, S. H. *Polymer* **2006**, 47, 1379-89.
- (25) Papageorgiou, G. Z.; Achilias, D. S.; Bikiaris, D. N.; Karayannidis G. P. *Thermochim Acta* **2005**, 427, 117-28.
- (26) Naffakh, M.; Marco, C.; Gómez, M. A.; Ellis, G.; Maser, W. K.; Benito, A., Martínez, M. T. *J. Nanosci. Nanotechnol.* **2009**, 9 (10), 6120-6126.
- (27) Marco, C.; Naffakh, M.; Gómez, M. A.; Santoro, G.; Ellis, G. *Polym. Compos.* **2011**, 32, 324–333.
- (28) Naffakh, M.; López, V.; Zamora, F.; Gómez, M. A. *Soft Mater.* **2010**, 8(4), 407-425.
- (29) Díez-Pascual, A. M.; Naffakh, M.; González-Domínguez J. M.; Martínez-Rubi, Y.; Ansón, A.; Martínez, M. T.; Simard, B.; Gómez, M. A. *Carbon* **2010**, 48, 3485-3499.

- (30) Liu, T.; Mo, Z.; Wang, S.; Zhang, H. *Polym. Eng. Sci.* **1997**, 37, 568-575.
- (31) Avrami, M. *J. Chem. Phys.* **1939**, 7, 1103-1112; *J. Chem. Phys.* **1940**, 8, 212-224; *J. Chem. Phys.* **1941**, 9, 177-184.
- (32) Ozawa, T. *Polymer* **1971**, 12, 150-158.
- (33) Dobrev, A.; Gutzow, I. *J. Non-Cryst. Solids* **1993**, 162, 1-12.
- (34) Dobrev, A.; Gutzow, I. *J. Non-Cryst. Solids* **1993**, 162, 13-25.
- (35) Kissinger, H. E. *J. Res. Natl. Bur. Stand.* **1956**, 57, 217-221.
- (36) Takhor, R. L. *Advances in Nucleation and Crystallization of Glasses*; American Ceramics Society: Columbus, 1971, p 166-172.

Figure captions:

Figure 1. DSC thermograms of dynamic crystallization of (a) iPP and (b) iPP/INT-MoS₂ (1 wt.%) obtained at indicated cooling rates.

Figure 2. Plots of degree of conversion (x) vs. temperature for (a) iPP and (b) iPP/INT-MoS₂ (1 wt.%) crystallized non-isothermally at various cooling rates.

Figure 3. Plots of degree of conversion (x) vs. time for (a) iPP and (b) iPP/INT-MoS₂ (1 wt.%) crystallized non-isothermally at various cooling rates; inset is the time needed to reach 50% of crystalline transformation.

Figure 4. Crystallization temperatures of iPP/INT-MoS₂ nanocomposites obtained at various cooling rates.

Figure 5. Liu plots of the dynamic crystallization of (a) iPP and (b) iPP/INT-MoS₂ (1 wt.%).

Figure 6. Dobrev plots for evaluating nucleation activity of INT-MoS₂ in iPP/INT-MoS₂ nanocomposites.

Figure 7. Kissinger and Takhor plots for evaluating effective energy barrier of iPP/INT-MoS₂ nanocomposites.

Figure 8. WAXS diffractograms of iPP/INT-MoS₂ (1 wt.%) obtained during cooling from the melt to room temperature at 10°C/min.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Table 1. Values of α and $f(T)$ versus conversion (x) based on Liu model for iPP/INT-MoS₂ nanocomposites.

INT-MoS ₂ content (wt.%)	x (%)	α	$f(T)$	φ	ΔE (kJ/mol) ^b	ΔE (kJ/mol) ^c
0.0	10	1.50	19.60	1.00	-246.6	-240.2
	30	1.42	22.70			
	50	1.38	24.69			
	70	1.36	27.06			
	90	1.35	31.65			
0.1	10	1.21	11.28	0.96	-259.9	-253.4
	30	1.19	13.41			
	50	1.18	14.80			
	70	1.18	16.04			
	90	1.18	18.08			
0.5	10	1.18	09.55	0.75	-271.5	-268.0
	30	1.18	11.55			
	50	1.19	12.96			
	70	1.20	14.53			
	90	1.23	17.25			
1.0	10	1.13	10.29	0.69	-255.8	-249.3
	30	1.12	12.22			
	50	1.12	13.50			
	70	1.13	14.90			
	90	1.15	17.22			

^a Nucleation activity calculated using Dovreba's equation.

^b Effective energy barrier calculated using Kissinger's equation.

^c Effective energy barrier calculated using Takhor's equation.