

Effects of dynamical cure and compatibilization on the morphology and properties of the PP/epoxy blends

X. L. Jiang^{*1}, K. Sun¹, Y. X. Zhang²

¹State Key Laboratory of Metal Matrix Composites, Shanghai Jiao Tong University, Shanghai, 200030, China

²Research Institute of Polymer Materials, Shanghai Jiao Tong University, Shanghai 200030, China

Received 28 February 2007; accepted in revised form 9 April 2007

Abstract. In this paper, effects of dynamical cure and compatibilization on the morphology and properties of the PP/epoxy blends were studied. The addition of maleic anhydride-grafted polypropylene (MAH-g-PP) and dynamical cure of epoxy by dicyanamide give rise to decrease the average diameter of epoxy particles in the PP/epoxy blends. The epoxy particles in the PP/epoxy blends act as effective nucleating agents, accelerating the crystallization of PP component. The dynamical cure and compatibilization increase the kinetic constant $K(T)$ of PP crystallization in the PP/epoxy blends. Dynamical cure of the epoxy resin leads to an improvement in the modulus and strength of the PP/epoxy blends, and the addition of MAH-g-PP results in an increase in the impact strength. Dynamic mechanical thermal analysis (DMTA) results indicate that the addition of MAH-g-PP improves the compatibility between PP and epoxy resin, and the storage modulus of the PP/epoxy blends increase by dynamical cure. Thermogravimetric analysis (TGA) results show dynamical cure of epoxy and addition of MAH-g-PP improved the thermal stability of the PP/epoxy blends. Wide-angle X-ray diffraction (WAXD) analysis shows that the PP/epoxy blends have the same crystalline structure as pure PP, indicating dynamical cure and compatibilization do not disturb the crystalline structure of the PP/epoxy blends.

Key words: polymer blends and alloys, polypropylene (PP), epoxy resin, dynamical cure, compatibilization

1. Introduction

Dynamical vulcanization is an effective way to prepare thermoplastic vulcanizates [1–3]. It is the process of vulcanizing an elastomer during melt-mixing with a molten plastic. This technology has led to a significant number of new thermoplastic elastomer products commercialized during the mid-to late-1980s [4–7]. Many thermoplastic vulcanizates are attributed to dynamic vulcanization of elastomers [8, 9]. However, as far as we know, there are few papers concerning dynamical vulcanization that is applied to thermoplastic resin/thermosetting resin blends [10].

The properties of polymeric materials strongly depend on their microstructure and crystal structure [11, 12]. PP has an important place among the syn-

thetic polymers because of its growing commercial applications. However, it exhibits relatively lower modulus and stiffness compared to common engineering plastics. Glass fiber and inorganic fillers are often used to enhance the modulus and stiffness of PP [13, 14].

Our laboratory has applied dynamical vulcanization to prepare a new type of PP/epoxy blends with the structure of crosslinked epoxy resin particles dispersed in the PP matrix [15–17]. The blends were prepared in the mixing chamber of a Haake rheometer RC90 through dynamical curing an epoxy resin by 2-ethylene-4-methane-imidazole (EMI-2,4) in the molten PP.

In this paper, the PP/epoxy blends were prepared by extrusion method, and dicyanamide was used as

*Corresponding author, e-mail: jx1110@sjtu.edu.cn
© BME-PT and GTE

a curing agent. As the epoxy resin and PP were immiscible, maleic anhydride-grafted polypropylene (MAH-g-PP) was acted as a compatibilizer, the effects of dynamical cure and compatibilization on morphology and properties of PP/epoxy blends were studied.

2. Experimental

2.1. Materials

PP, F401 was produced by Yangzi Petrochemical Co., Ltd. (China), with a melt flow index (MFI) of 1.9 dg/min (230°C, 2.16 kg). Diglycidyl ether of bisphenol-A resin with epoxy equivalent weight (EEW) of 2000 g/mol, was supplied by Shanghai Resin Co., Ltd. (China). The curing agent, dicyanamide, was supplied by Shanghai Chemical Agent Company (China). Maleic anhydride-grafted polypropylene (MAH-g-PP) with a MAH content of 1% was prepared by Shanghai Sunny New Technology Development Co., Ltd. (China), and its MFI is 6.8 dg/min (230°C, 2.16 kg).

2.2. Sample preparation

The PP/epoxy blends were prepared by twin-screw extruder. Before extruding, MAH-g-PP and the epoxy resin were dried at 80°C under vacuum for about 8 h. The content of dicyanamide is 2 parts per 100 parts by the weight of epoxy resin. The temperature profile of the extruder was 140°C, 160°C, 180°C and 200°C, and the rotation speed of the screws was 60 rpm. The strips from the extruder were cut into granules about 4 mm long after cooling in a water bath. The composition was moved out and compression-moulded in a press at 195°C for 10 min, then cold pressed to give samples for testing.

2.3. Scanning electron microscope (SEM) analysis

A scanning electron microscope (SEM, HITACHI-S-2150, Japan) was used to examine the morphology of the blends. Samples were fractured in liquid nitrogen and covered with a thin gold layer for further observation. The number-average particle diameter (d_n) was calculated from a minimum of 100 particles as $d_n = \sum n_i d_i / \sum n_i$ where n_i is the number of particles with a diameter d_i .

2.4. DSC analysis

Crystallization behavior was analyzed using a Perkin-Elmer DSC (Paris 1, USA) in a nitrogen atmosphere. Samples of about 4 mg were taken from the moulded plaques. Isothermal crystallization kinetics was performed as follows: the samples were heated to 200°C at a heating rate of 10°C/min and maintained at this temperature for 5 min in order to eliminate any previous thermal history and then were cooled rapidly (100°C/min) to the crystallization temperature, and maintained at that temperature till the time necessary for the complete crystallization of the PP matrix.

2.5. Measurements of mechanical properties

The tensile properties were measured using an Instron 4465 (UK) tensile tester at a crosshead speed of 20 mm/min according to ASTM D638. Notched Izod impact strengths were determined using a Ray-Ran Universal Pendulum Impact Tester (UK) at an impacting pendulum speed of 3.5 m/s, according to ASTM D256. Flexural properties were measured using the Instron 4465 and a three-point-loading rig, and the central head was loaded on the specimen at a speed of 1.7 mm/min according to ASTM D790. In each of the tests, at least five samples were tested, and the average results were reported.

2.6. Dynamic mechanical thermal analysis (DMTA)

Dynamic mechanical thermal analysis (DMTA) was carried out in a Dynamic Mechanical Thermal Analyser (Rheometrics Scientific DMTA IV, USA). Measurements were performed in the tension mode at a frequency of 1 Hz over a temperature range of –40°C to 150°C, and at a heating rate of 3°C/min. The strain amplitude remained at 0.01%.

2.7. Thermogravimetric analysis (TGA)

The thermogravimetry was carried out in a Perkin-Elmer TGA7 (USA). The samples were scanned from 30°C to 800°C at a heating rate of 20°C/min in a nitrogen atmosphere.

2.8. Wide-angle X-ray diffraction (WAXD) analysis

The X-ray diffraction experiments were performed using a Rigaku Dmax-rC diffractometer (Japan) with Cu target and a rotating anode generator operated at 40 kV and 100 mA. The scanning rate was 2°/min from 5° to 35°. The sample for WAXD measurement was prepared by compression-moulded at 200°C and 5 MPa.

3. Results and discussion

3.1. Morphology of the PP/epoxy blends

Figure 1 shows SEM micrographs of the fracture surfaces of the PP/epoxy (80/20), PP/MAH-g-PP/epoxy (75/5/20), dynamically cured PP/epoxy (80/20) and dynamically cured PP/MAH-g-PP/epoxy (75/5/20) blends. For the PP/epoxy (80/20) blend (Figure 1a), the epoxy resin is dispersed as spherical particles with a number-average diameter (d_n) of about 6 μm in the PP matrix, and the boundaries between the dispersed phase and the PP matrix are distinct. While for the PP/MAH-g-PP/epoxy (75/5/20) blend (Figure 1b), fine epoxy particles with d_n of about 1.0 μm are distributed in the PP matrix. The small particle size should be related to the presence of 5% MAH-g-PP. It can be

concluded that MAH-g-PP improves the compatibility between PP and the epoxy resin. Figure 1c, d shows the fracture morphology of the dynamically cured PP/epoxy (80/20) and dynamically cured PP/MAH-g-PP/epoxy (75/5/20) blends. The d_n of epoxy particles in the dynamically cured PP/MAH-g-PP/epoxy (75/5/20) blend is much smaller than that of dynamically cured PP/epoxy (80/20) blend because of the compatibility of MAH-g-PP, and is about 0.5 μm which is also slightly smaller than that of the PP/MAH-g-PP/epoxy (75/5/20) blend. The dynamically cured PP/epoxy (80/20) blend has the finer domains compared to the PP/epoxy (80/20) blend. The result shows that dynamical cure could further decrease an average diameter of epoxy particles in the PP/epoxy blends, which is attributed to the aggregation of the uncured epoxy particles in the blends and results in an increase in an average diameter of the epoxy particles.

The FTIR spectra of the MAH-g-PP, epoxy resin and PP/MAH-g-PP/epoxy (75/5/20) blend are shown in Figure 2, the characteristic band of the epoxy ring of the epoxy resin (Figure 2a) was observed at 921 cm^{-1} , and the absorption peak of the C–O–C appeared at 1259 cm^{-1} . Furthermore the characteristic band assigned to the –CH₂–stretching of the epoxide ring was observed at

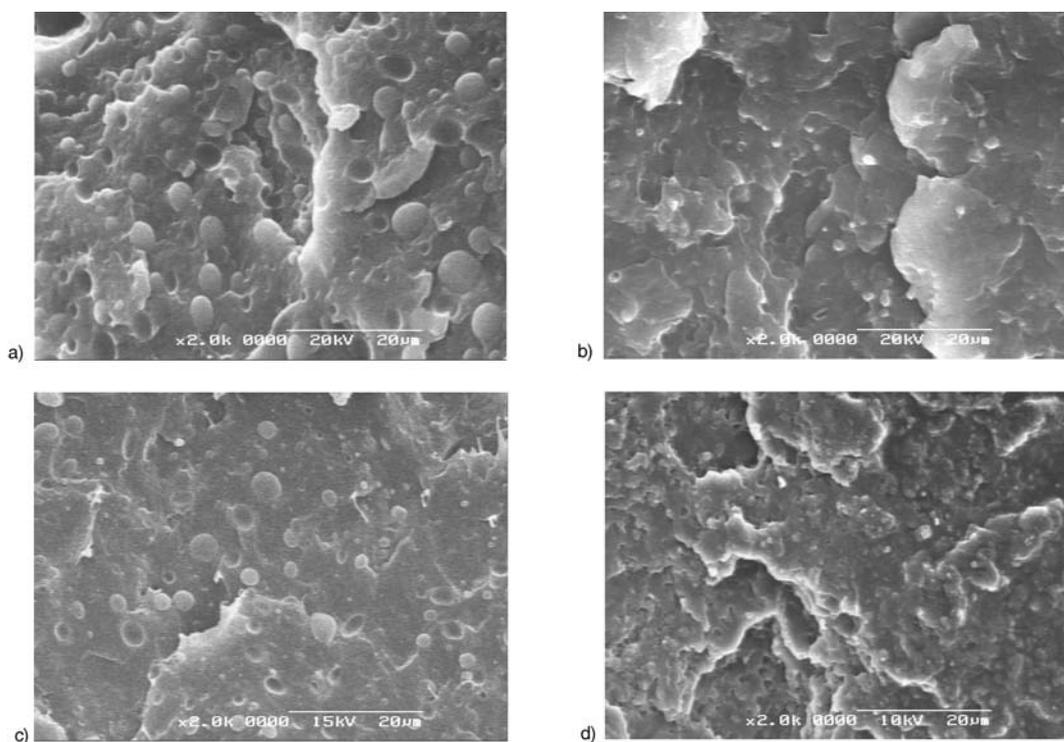


Figure 1. SEM micrographs of the PP/epoxy blends. (a) PP/epoxy = 80/20, (b) PP/MAH-g-PP/epoxy = 75/5/20, (c) dynamically cured PP/epoxy = 80/20, (d) dynamically cured PP/MAH-g-PP/epoxy = 75/5/20

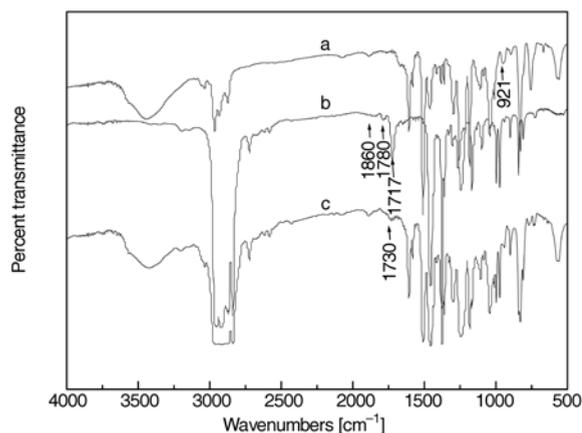


Figure 2. FTIR spectra of (a) epoxy resin (b) MAH-g-PP (c) PP/MAH-g-PP/epoxy = 75/5/20

2852–3057 cm^{-1} . The spectrum of MAH-g-PP (Figure 2b) shows the characteristics of a saturated ring anhydride. The bands at 1860 cm^{-1} and 1780 cm^{-1} are attributed to the symmetrical and asymmetrical stretching modes of C=O in the maleic anhydride and the bands at 1717 cm^{-1} are attributed to the C=O bond of maleic acid which is come from the hydrolyzate of MAH. In the case of the PP/MAH-g-PP/epoxy (75/5/20) blend (Figure 2c), a little higher absorption peak (1731 cm^{-1}) was seen compared with the absorption peak of the C=O of maleic acid at 1717 cm^{-1} in the spectrum of MAH-g-PP, which is come from the C=O of the ester group, the intensity of the peak attributed to the epoxide ring at 921 cm^{-1} also decreased. As MAH-g-PP has active maleic anhydride groups, the functional groups of MAH-g-PP react with the hydroxyl or epoxy groups of epoxy resin. A simple scheme of reaction between MAH-grafted PP and the

epoxy resin was shown in Figure 3. We thought that the reactions between the groups take place in the PP/MAH-g-PP/epoxy blends and lead to an improved compatibility between PP and epoxy resin.

3.2. Isothermal crystallization kinetics of the PP/epoxy blends

The crystallization kinetics of polymers under isothermal conditions for various modes of nucleation and growth can be well approximated by the known Avrami equation [18, 19]. The general form of the Equation (1) is:

$$X(t) = 1 - \exp(-K(T)t^n) \tag{1}$$

where $X(t)$ is the relative crystallinity at different crystallization time, the Avrami exponent n is a constant depending on the mechanism of nucleation and the form of crystal growth, $K(T)$ is a constant related to nucleation and growth parameters. $X(t)$ can be calculated according to the Equation (2).

$$X(t) = \frac{Q_t}{Q_\infty} = \frac{\int_0^t \frac{dH}{dt} dt}{\int_0^\infty \frac{dH}{dt} dt} \tag{2}$$

where Q_t and Q_∞ are the heat generated at time t and infinite time t_∞ , respectively, and dH/dt is heat evolution rate.

The Avrami equation can be written as (3):

$$\log[-\ln(1 - X(t))] = n \cdot \log t + \log K(T) \tag{3}$$

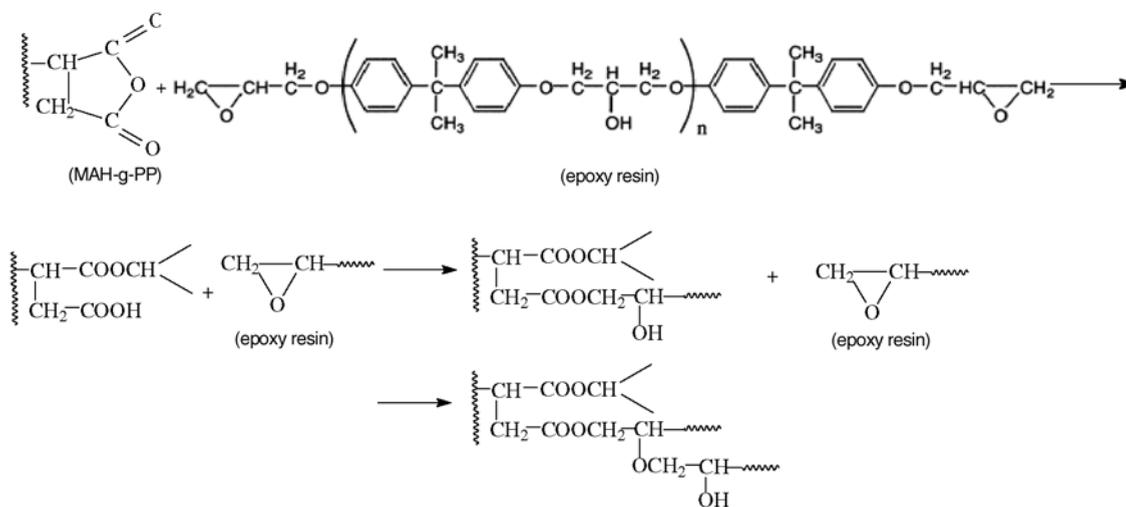


Figure 3. A simple scheme of reaction between MAH-g-PP and the epoxy resin

From a graphic representation of $\log[-\ln(1 - X(t))]$ versus $\log t$, the Avrami exponent n (slope of the straight line) and the crystallization kinetic constant $K(T)$ (intersection with the y-axis) can be obtained. The half time of PP crystallization, $t_{1/2}$, is defined as the time at which the relative crystallinity is 50%. Figure 4 shows that the relative crystallinity $X(t)$ changes with increasing T_c . Usually, $t_{1/2}$ is

employed to characterize the rate of crystallization directly. The greater the value of $t_{1/2}$ is, the smaller the rate of the crystallization. Plots of $\log[-\ln(1-X(t))]$ versus $\log t$ are shown in Figure 5. The results from Figure 5 are listed in Table 1. The kinetic constant $K(T)$ of PP crystallization in the PP/epoxy blends is higher than that of PP, which suggests that the epoxy particles act as effec-

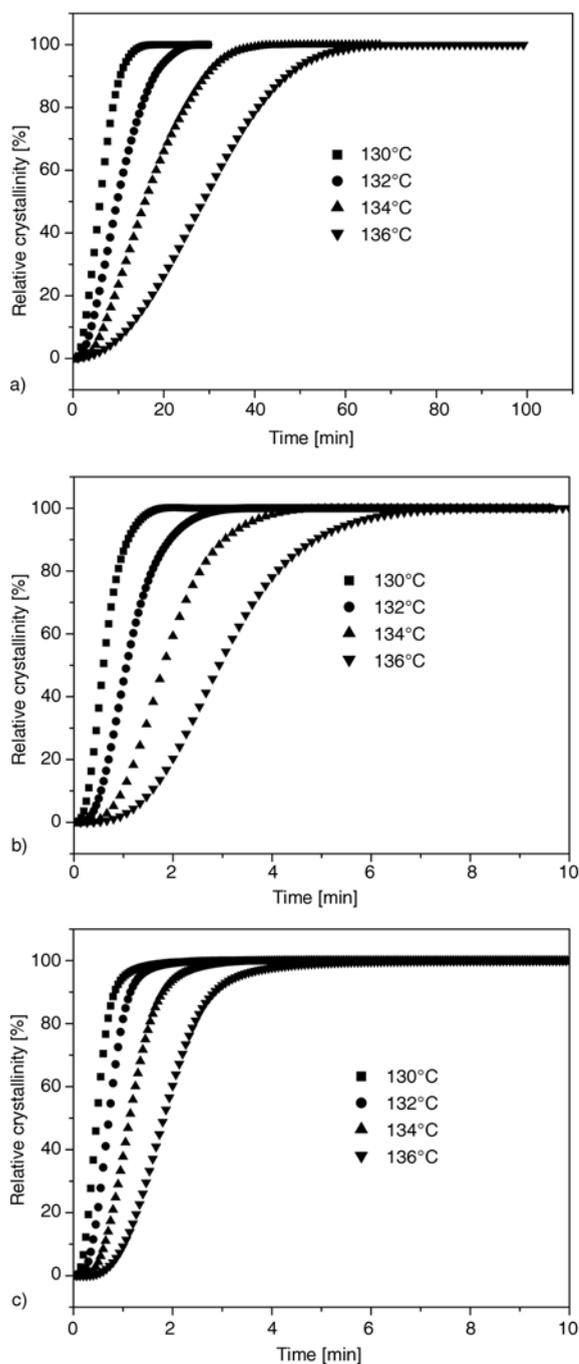


Figure 4. Development of relative crystallinity with time for isothermal crystallization. (a) PP; (b) PP/MAH-g-PP/epoxy = 75/5/20; (c) dynamically cured PP/MAH-g-PP/epoxy = 75/5/20

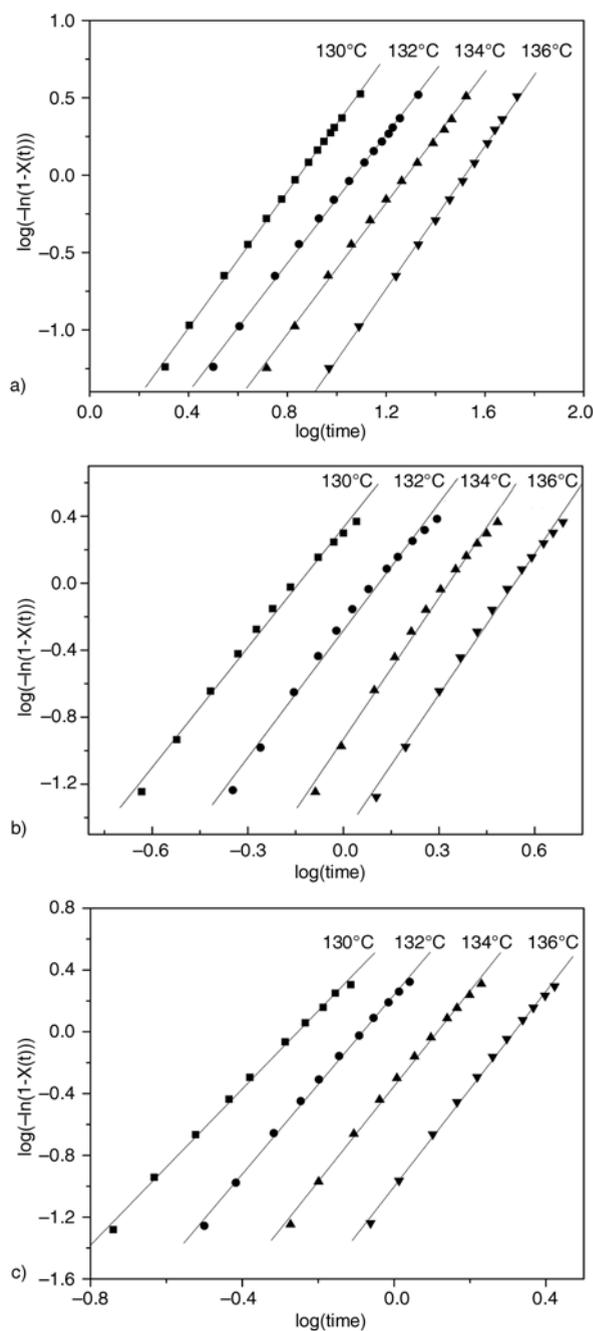


Figure 5. Avrami plots of PP and dynamically cured PP/epoxy blends at different crystallization temperature. (a) PP; (b) PP/MAH-g-PP/epoxy = 75/5/20; (c) dynamically cured PP/MAH-g-PP/epoxy = 75/5/20

Table 1. Kinetic parameters of the PP and the PP/epoxy blends

Compositions	T _c [°C]	K(T)	n	t _{1/2} [min]
PP	130	0.065	2.09	5.34
	132	0.006	2.14	7.86
	134	0.002	2.20	13.80
	136	0.0003	2.30	30.97
PP/epoxy = 80/20	130	0.342	3.00	1.24
	132	0.085	3.08	1.92
	134	0.011	3.16	3.44
	136	0.004	3.29	5.42
PP/MAH-g-PP/epoxy = 75/5/20	130	2.152	2.78	0.61
	132	0.523	2.83	1.07
	134	0.117	2.91	1.81
	136	0.032	3.05	2.93
dynamically cured PP/epoxy=80/20	130	1.444	2.76	0.78
	132	0.185	2.98	1.51
	134	0.086	3.15	2.01
	136	0.017	3.29	3.05
dynamically cured PP/MAH-g-PP/epoxy = 75/5/20	130	4.37	2.87	0.46
	132	1.75	2.94	0.77
	134	0.44	3.10	1.27
	136	0.10	3.20	1.94

tive nucleating agents, accelerating the crystallization of PP component in the blends. $K(T)$ of PP crystallization in the PP/MAH-g-PP/epoxy (75/5/20) and dynamically cured PP/MAH-g-PP/epoxy (75/5/20) are higher than that in the PP/epoxy (80/20) and dynamically cured PP/epoxy (80/20), and the dynamically cured PP/MAH-g-PP/epoxy (75/5/20) has a minimum of $K(T)$ in all the PP/epoxy blends. The result shows that the dynamical cure and compatibilization further accelerated the crystallization of PP component in the PP/epoxy blends because the smaller size of epoxy particles act as the more effective the nucleating agents for PP crystallization. Nano-fillers often act as more effective nucleating agents for PP crystallization compared with other components [13, 20].

It is well known that the Avrami exponent n depends on the nucleation process and the geometry of the growing crystals. As shown in Table 1, the n value is about 3 for the PP/epoxy blends,

which suggests a three-dimensional heterogeneous crystal growth in a spherical form of PP. As shown in Table 1, the PP/epoxy blends show a noticeable decrease in the half time of PP crystallization ($t_{1/2}$) compared with the pure PP, which is attributed to a nucleating effect of the epoxy particles on the PP crystallization. $t_{1/2}$ increases with increasing crystallization temperature at a given blend composition.

3.3. Mechanical properties

Table 2 shows the effects of dynamical cure and compatibilization the mechanical properties of the PP/epoxy blends. The addition of 20 wt% epoxy resin to the PP matrix improves the flexural modulus but reduces the impact strength, tensile strength, and elongation at break because of the poor compatibility between PP and the epoxy resin. Through the addition of 5 wt% MAH-g-PP (used as a compatibilizer), the PP/MAH-g-PP/epoxy (75/5/20) has a higher modulus and tensile strength than the PP/epoxy (80/20). The dynamically cured PP/epoxy (80/20) has the higher flexural modulus (1960 MPa) and tensile strength (38.8 MPa), which increase by 14% and 50%, respectively, in comparison with those of PP/epoxy (80/20), but the impact strength of the blend is lower than that of the PP/MAH-g-PP/epoxy (75/5/20). The dynamically cured PP/MAH-g-PP/epoxy (75/5/20) has best mechanical properties in all the PP/epoxy blends. The result shows that dynamical cure of the epoxy resin led to an improvement in the modulus and strength of the PP/epoxy blends, and the addition of MAH-g-PP results in the increases in the impact strength.

3.4. DMTA analysis

DMTA was used to determine the miscibility of the blends by investigating the glass transition temperatures (T_g) of the blend components. The loss factor ($\tan\delta$) and the storage modulus (E') are shown as

Table 2. Mechanical properties of PP and the PP/epoxy blends

Compositions	Impact strength [J/m]	Tensile strength [MPa]	Elongation at break [%]	Tensile modulus [MPa]	Flexural modulus [MPa]
PP	30±2	30.8±1.5	300±35	1357±44	1250±36
PP/epoxy (80/20)	20±3	24.2±1.2	11±3	1724±51	1650±42
PP/MAH-g-PP/epoxy (75/5/20)	31±2	38.6±1.7	22±4	1872±32	1792±29
dynamically cured PP/epoxy (80/20)	22±2	38.8±1.3	11±3	2097±38	1960±47
dynamically cured PP/MAH-g-PP/epoxy (75/5/20)	33±2	42.3±1.6	15±4	2268±29	2140±34

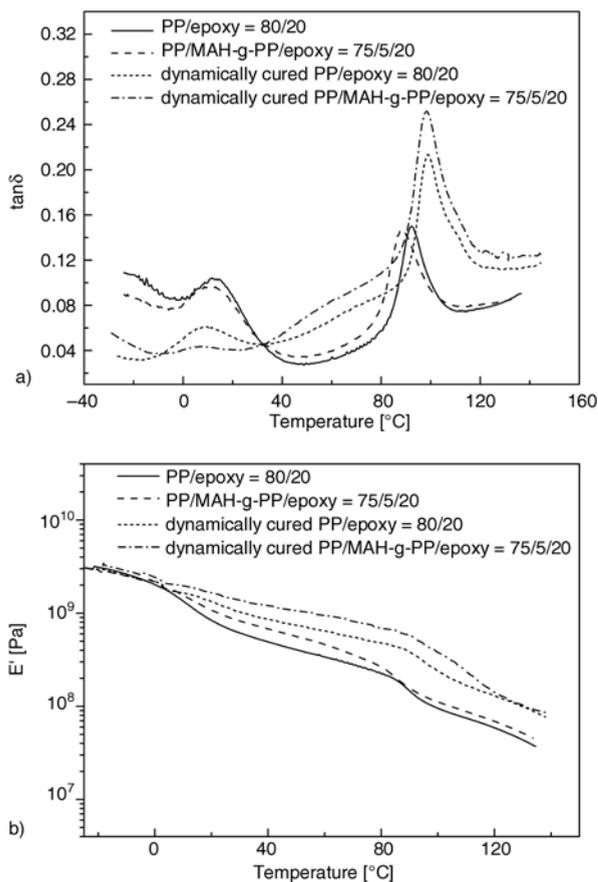


Figure 6. Curves of dynamical properties versus temperature for the PP/epoxy blends. (a) $\tan\delta$ -temperature; (b) E' – temperature

functions of temperature for the PP/epoxy blends in Figure 6. Figure 6a shows the loss factor-temperature ($\tan\delta-T$) curves for the blends. They indicate two obvious glass transition peaks, which confirm the presence of two phases. For the PP/epoxy (80/20) blend, the peak at about 12.5°C is the glass transition peak of PP, while the glass transition peak of the epoxy resin is at 90.4°C. The glass transition peak of the epoxy resin in the PP/MAH-g-PP/epoxy (75/5/20) blend moved to a lower temperature on the addition of 10 wt% MAH-g-PP, and this suggests that the compatibility between PP and epoxy resin was improved. The T_g values of the epoxy resin in the dynamically cured PP/epoxy (80/20) and dynamically cured PP/MAH-g-PP/epoxy (75/5/20) blends were higher than that of the epoxy resin in the PP/epoxy (80/20) and PP/MAH-g-PP/epoxy (75/5/20) blends, a shift in the T_g of the epoxy resin in the blends to a higher temperature suggests that dynamic cure results in a decrease in the molecular mobility of the epoxy resin.

Table 3. DMTA analysis results of the PP/epoxy blends

Compositions	T_g of PP [°C]	T_g of epoxy [°C]	E' at 25°C [Pa]
PP/epoxy = 80/20	12.5	90.4	$6.89 \cdot 10^8$
PP/MAH-g-PP/epoxy = 75/5/20	12.2	85.5	$8.09 \cdot 10^8$
dynamically cured PP/epoxy = 80/20	12.9	100.6	$9.24 \cdot 10^8$
dynamically cured PP/MAH-g-PP/epoxy = 75/5/20	12.2	99.7	$1.03 \cdot 10^9$

Figure 6b shows that the storage modulus (E') of the dynamically cured PP/MAH-g-PP/epoxy (75/5/20) and dynamically cured PP/epoxy (80/20) are obviously higher than that PP/epoxy (80/20) and PP/MAH-g-PP/epoxy (75/5/20), the dynamically cured PP/MAH-g-PP/epoxy (75/5/20) has highest E' , but the PP/epoxy (80/20) blend has the lowest E' . The result shows that the interaction between PP and epoxy resin was strengthened by the addition of the MAH-g-PP, dynamical cure of epoxy resin increases the storage modulus (E') of the PP/epoxy blends (Table 3).

3.5. TGA analysis

One of the most widely accepted methods for studying the thermal properties of polymeric materials is thermogravimetry, which by means of integral and derivative thermogravimetric curves provide information about the nature and extent of degradation of polymeric materials [21]. Thermograms of the PP and PP/epoxy blends are shown in Figure 7. The degradation of PP started at 367°C and finished at 448°C. In the case of the PP/epoxy (80/20), the incorporation of 20 wt% epoxy resin increases the initial degradation temperature (T_0) from 367°C to 402°C. The T_0 of the PP/MAH-g-PP/epoxy (75/5/20) blend is higher than that of the PP/epoxy (80/20) blend, but lower than that of dynamically cured PP/epoxy (80/20) blend. The dynamically cured PP/MAH-g-PP/epoxy (75/5/20) blend has the highest initial degradation temperature (T_0) in the all PP/epoxy blends, the T_0 of the blend is about 429°C, and increases by 20°C compared with the PP/epoxy (80/20) blend (shown in Table 4). The temperature of maximum rates of mass losses (T_{max}) for PP and the PP/epoxy blends were obtained by derivative thermogravimetric (DTG) curves (shown in Figure 7b), and T_{max} has

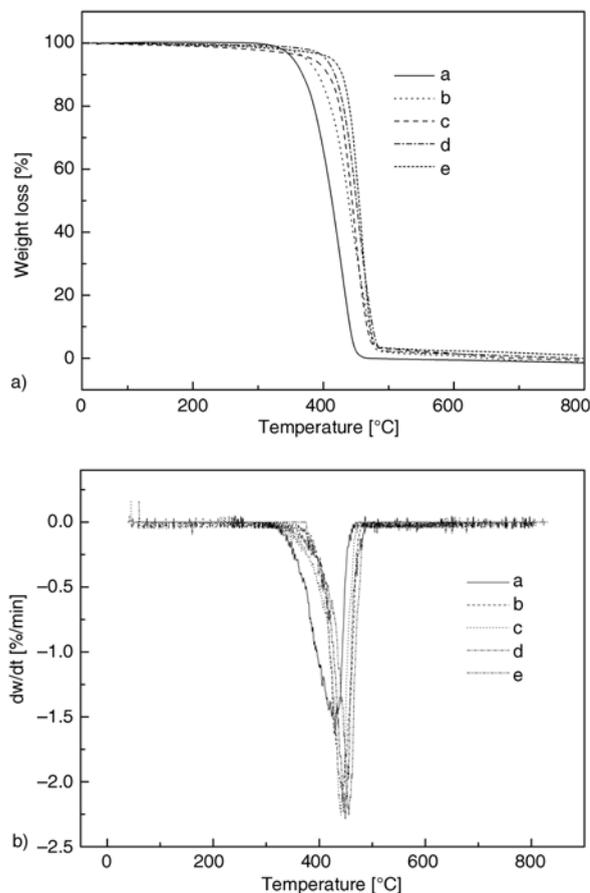


Figure 7. TG (a) and DTG (b) curves of the PP and the PP/epoxy blends. (a) PP; (b) PP/epoxy=80/20; (c) PP/MAH-g-PP/epoxy = 75/5/20; (d) dynamically cured PP/epoxy = 80/20; (e) dynamically cured PP/MAH-g-PP/epoxy = 75/5/20

Table 4. TG and DTG analysis results of PP and the PP/epoxy blends (T_0 : initial degradation temperature; T_f : final degradation temperature; T_{max} : temperature of maximum rate of mass loss)

Compositions	T_0 [°C]	T_f [°C]	T_{max} [°C]
PP	367	448	424
PP/epoxy = 80/20	405	480	431
PP/MAH-g-PP/epoxy = 75/5/20	417	485	436
dynamically cured PP/epoxy = 80/20	425	492	441
dynamically cured PP/MAH-g-PP/epoxy = 75/5/20	430	498	448

the same tendency as T_0 . All the degradation of PP/epoxy blends took place in one step, in the same way as for PP. The results show that the incorporation of the epoxy resin into the PP could improve the thermal stability of PP, and the dynamic cure of epoxy resin obviously could further improve the thermal stability. George [21] suggested that the thermal degradation of polymer blends depends not only on the thermal stability of the components but

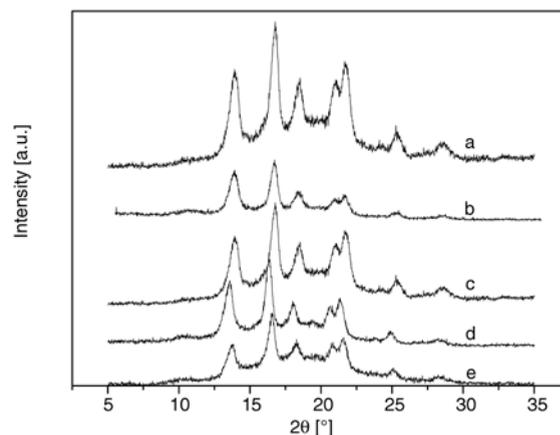


Figure 8. Crystal structure of PP and the PP/epoxy blends. (a) PP; (b) PP/epoxy = 80/20; (c) PP/MAH-g-PP/epoxy = 75/5/20; (d) dynamically cured PP/epoxy = 80/20; (e) dynamically cured PP/MAH-g-PP/epoxy = 75/5/20

also on the morphology and the extent of interaction between the phases.

3.6. Wide-angle X-ray diffraction (WAXD) analysis

In order to investigate whether the crystalline structure formed by one component of the blend can be affected by the other component or the compatibilizer. X-ray diffraction studies were made on the corresponding PP and the PP/epoxy blends. Figure 8 shows the WAXD patterns of PP, PP/epoxy (80/20), PP/MAH-g-PP/epoxy (75/5/20), dynamically cured PP/epoxy (80/20) and dynamically cured PP/MAH-g-PP/epoxy (75/5/20). Several reflections in both the PP/epoxy blends and PP are observed at $2\theta = 13.9^\circ, 16.7^\circ, 18.3^\circ, 20.9^\circ, 21.8^\circ$, which belong to the identical monoclinic α form of the PP component. The result shows that the dynamical cure and compatibilization do not disturb the crystalline structure of PP in the PP/epoxy blends.

4. Conclusions

The PP/epoxy blends compatibilized with MAH-g-PP have finer domains compared with the PP/epoxy blends, and dynamical cure could further decrease an average diameter of epoxy particles in the PP/epoxy blends. Isothermal crystallization kinetics show that the dynamical cure and compatibilization give a rise to the number of smaller epoxy particles, further accelerating the crystalliza-

tion of PP component in the PP/epoxy blends. Dynamical cure of the epoxy resin leads to an improvement in the tensile strength and flexural modulus of the PP/epoxy blends, and the addition of MAH-g-PP results in an increase in the impact strength. DMTA results indicate that the compatibility between PP and epoxy resin is improved by the addition of MAH-g-PP, and dynamical cure of epoxy resin obviously increase the storage modulus of the PP/epoxy blends. TGA results show the dynamical cure and compatibilization could improve the thermal stability of the PP/epoxy blends. The crystalline structure of PP in the PP/epoxy blends is the same as that of PP, and the dynamical cure and compatibilization do not disturb the crystalline structure of PP in the blends, a similar result was reported by Zhang [22].

References

- [1] Geessler A. M.: Process for preparing a vulcanized blend of crystalline polypropylene and chlorinated butyl rubber. US Patent, 3037954, USA (1962).
- [2] Fischer W. K.: Thermoplastic blend of partially cured monoolefin copolymer rubber. US Patent 3758643, USA (1971).
- [3] Coran A. Y., Das B., Patel R. P.: Thermoplastic vulcanizates of olefin rubber and polyolefin resin, US Patent, 4130535, USA (1978).
- [4] Coran A. Y., Patel R.: Rubber-thermoplastic compositions. Part I. EPDM-polypropylene thermoplastic vulcanizates. *Rubber Chemistry and Technology*, **53**, 141–150 (1980).
- [5] Coran A. Y., Patel R.: Rubber-thermoplastic compositions. Part III. Predicting elastic moduli of melt mixed rubber-plastic blends. *Rubber Chemistry and Technology*, **54**, 91–100 (1981).
- [6] Coran A. Y., Patel R. P.: Thermoplastic compositions of high unsaturation diene rubber and polyolefin resin. US Patent 4104210, USA (1975).
- [7] Coran A. Y.: Thermoplastic elastomeric rubber-plastic blends. in 'Handbook of elastomers: new developments and technology' (eds.: Bhowmick A. K., Stephens H. L.) Marcel Dekker, New York, 249–260 (1988).
- [8] Huang H., Yang J. L., Liu X., Zhang Y. X.: Dynamically vulcanized ethylene propylene diene terpolymer/nylon thermoplastic elastomers. *European Polymer Journal*, **38**, 857–861 (2002).
- [9] Wang Z. J., Zhang X. F., Zhang Y., Zhang Y. X., Zhou W.: Effect of dynamic vulcanization on properties and morphology of nylon/SAN/NBR blends: A new compatibilization method of nylon/ABS blends. *Journal of Applied Polymer Science*, **87**, 2057–2062 (2003).
- [10] Wan C., Patel S. H., Xanthos M.: Reactive melt modification of PP with a crosslinkable polyester. *Polymer Engineering and Science*, **43**, 1276–1288 (2003).
- [11] Avalos F., López-Manchado M. A., Arroyo M.: Crystallization kinetics of polypropylene: 1. Effect of small additions of low-density polyethylene. *Polymer*, **37**, 5681–5688 (1996).
- [12] Arroyo M., Zitzumbo R., Avalos F.: Composites based on PP/EPDM blends and short fibers I Morphology/behaviour relationship. *Polymer*, **41**, 6351–6359 (2000).
- [13] Chan C-M., Wu J., Li J-X., Cheung Y-K.: Polypropylene/calcium carbonate nanocomposites. *Polymer*, **43**, 2981–2992 (2002).
- [14] Lee N-J., Jang J.: The effect of fibre content on the mechanical properties of glass fibre mat/polypropylene composites. *Composites Part A: Applied Science and Manufacturing*, **30**, 815–822 (1999).
- [15] Jiang X. L., Zhang Y., Zhang Y. X.: Study of dynamically cured PP/MAH-g-EPDM/epoxy blends. *Polymer Testing*, **23**, 259–265 (2004).
- [16] Jiang X. L., Zhang Y., Zhang Y. X.: Study of dynamically cured PP/MAH-g-PP/talc/epoxy composites. *Journal of Applied Polymer Science*, **99**, 2752–2758 (2006).
- [17] Jiang X. L., Huang H., Zhang Y., Zhang Y. X.: Dynamically cured polypropylene/epoxy blends. *Journal of Applied Polymer Science*, **92**, 1437–1448 (2004).
- [18] Avrami M.: Kinetics of phase change-I. General theory. *Journal of Chemistry and Physics*, **7**, 1103–1112 (1939).
- [19] Avrami M.: Granulation, phase change and microstructure kinetics of phase change. III. *Journal of Chemistry and Physics*, **9**, 177–184 (1941).
- [20] Xu W. B., Ge M. L., He P. S.: Nonisothermal crystallization kinetics of polypropylene /montmorillonite nanocomposites. *Journal of Polymer Science Part B: Polymer Physics*, **40**, 408–414 (2002).
- [21] Remiro P. M., Cortazar M., Calahorra E., Calafel M. M.: The effect of crosslinking and miscibility on the thermal degradation of an uncured and an amine-cured epoxy resin blended with poly(ϵ -caprolactone). *Polymer Degradation and Stability*, **78**, 83–93 (2002).
- [21] George S., Varughese K. T., Thomas S.: Thermal and crystallization behavior of isotactic polypropylene/nitrile rubber blends, *Polymer*, **41**, 5485–5503 (2000).
- [22] Zhang M. L., Liu Y., Zhang X. H. Jianming Gao, Huang F., Song Z. H., Wei G., Qiao J. L.: The effect of elastomeric nano-particle on the mechanical properties and crystallization behavior of polypropylene. *Polymer*, **43**, 5133–5138 (2002).