



A naphthyl-imide-based epoxy resin: Cure kinetics and application in carbon fiber reinforced composites

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Abstract

A novel heat-resistant epoxy resin based on N, N'-bis(5-hydroxy-1-naphthyl) pyromellitic diimide was prepared and its cure kinetics with 4,4-diaminodiphenylsulfone (DDS) was investigated by differential scanning calorimetry (DSC) under non-isothermal and isothermal conditions. Under non-isothermal condition, the effective activation energy calculated from the advanced isoconversional method (AICM) varies with curing conversion, which is different from that obtained by Kissinger's model. This should be attributed to the formation of highly crosslinked network later in the curing stage. The isothermal curing process at different temperatures could be well fitted by Kamal's model in the initial curing stage but deviates subsequently. The deviation is corrected by introducing a diffusion factor in Kamal's model. In addition, the naphthyl-imide epoxy resin is used to prepare carbon fiber reinforced composites and their applications were explored. The composites exhibit a high glass transition temperature, low moisture absorption, sufficient flame retardance and especially very low tensile strength loss at high temperature.

Keywords

epoxy resin, cure kinetics, composites

1. Introduction

Epoxy resins have many advantages including excellent chemical resistance, good mechanical properties, good thermal and dimensional stability, and so they have been widely used in laminating, adhesives, surface coating and advanced composites. However, conventional epoxy resins are unable to satisfy the requirements of some applications such as integrated circuit packaging and aeronautic composite materials which require extremely high thermal resistance.¹ It is thus indispensable to design and synthesize heat-resistant epoxy resins for these applications.

Many approaches have been reported to improve the thermal resistance of epoxy resins by changing structures of backbone. The introduction of naphthalene ring into the epoxy skeleton is an effective way to increase the glass transition temperature and thermal stability.^{1–9} In addition, polymers containing imide structures are well known for their excellent heat resistance due to the thermal stable imide linkage. The incorporation of imide structures into epoxy networks can improve the thermal properties of cured resins. However, most of the researches were focused on preparing of the imide group containing curing agents^{10–14} and

blending epoxy resins with functionalized polyimides,¹⁵ few reports are found about modifying the skeleton of epoxy resins with an imide group.¹⁶ In our previous study, a novel heat-resistant epoxy resin based on N, N'-bis(5-hydroxy-1-naphthyl)pyromellitic diimide has been synthesized. The combination of naphthyl and imide structure could increase the rigidity of backbone and facilitate the thermal properties of cured resins, which offers great improvement in glass transition temperature and thermal stability of epoxy resin.¹⁷

As a novel type of epoxy resin, it is significant to study cure behaviors and mechanism dependence on the molecular structure, which could give essential guidance for further applications. The curing of epoxy resins involves

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monomers or pre-polymers with low molecular weight into three-dimensional-structure networks. The kinetic of curing reaction determines network morphology, which dictates physical and mechanical properties of the cured product.¹⁸ Differential scanning calorimetry (DSC) is the most commonly used experimental method to obtain curing degree and reaction rate, which allows direct measurement of heat flow that is considered to be proportional to the reaction process. The cure kinetics models are generally developed by analyzing the experimental data obtained from isothermal or dynamic DSC measurement. Kamal's model¹⁹ has been commonly applied to study isothermal DSC curve, a good fit of the experimental data could be found both at early stages and at later diffusion-controlled stages when a diffusion factor was introduced. Kissinger's model^{20, 21} is a simple and convenient method to calculate the activation energy from non-isothermal DSC measurement. Furthermore, Vyazovkin et al.^{22,23} reported a model-free kinetics theory of the advanced isoconventional method (AICM), which is associated with changes in the mechanism as the activation energy changes. The calculated results from these methods could help in understanding the complex reaction mechanism.

In this study, the cure kinetics of *N,N'*-bis(5-hydroxy-1-naphthyl)pyromellitic diimide containing epoxy resin with 4,4'-diaminodiphenylsulfone (DDS) was investigated by DSC under isothermal and non-isothermal conditions. The reasons for the differences in the values of activation energies calculated from Kamal's model, Kissinger's model and AICM are discussed. The mechanism of cure reactions are also investigated on the basis of the DSC results. Carbon fiber reinforced composites were prepared from the resin and their thermal and mechanical properties were evaluated.

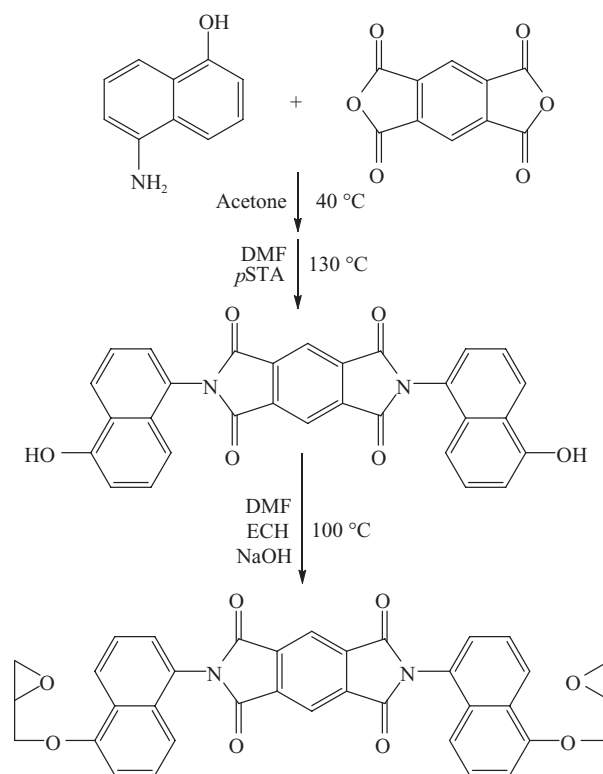
2. Experimental details

2.1. Materials

5-Amino-1-naphthol purchased from Acros, pyromellitic acid dianhydride and *p*-toluene sulfonic acid (*p*TSA) from Sinopharm Chemical Reagent Co. Ltd, China, and epichlorohydrin (ECH) from Tianjin Bodi Chemical Reagent Co. Ltd were used without further purification. 4,4'-Diaminodiphenylsulfone obtained from Yinsheng Chemicals Co. Ltd, China, was used as the curing agent. Diglycidyl ether of bisphenol A (DGEBA) epoxy resin DER 330 with epoxy equivalent weight of 181 g/equiv. was kindly supplied by Dow Chemical. Toray T300 3 K carbon fiber was used to prepare composites to evaluate the thermal and mechanical properties. All solvents and other chemicals were of reagent grade.

2.2. Synthesis

The epoxy monomer was prepared through the condensation reaction between 5-amino-1-naphthol and pyromellitic



Scheme 1. Synthesis of *N,N'*-bis(5-hydroxy-1-naphthyl)pyromellitic diimide-based epoxy resin.

acid dianhydride, then the monomers reacted with epichlorohydrin to obtain the epoxy resin based on *N,N'*-bis(5-hydroxy-1-naphthyl)pyromellitic diimide.¹⁷ Scheme 1 shows the synthesis route and molecular structure of the novel epoxy resin.

2.3. Curing procedure

The *N,N'*-bis(5-hydroxy-1-naphthyl)pyromellitic diimide-based epoxy resin and DDS were used in a 1:1 equivalent ratio and some were dissolved in the mixture of *N,N*-dimethylformamide/acetone at room temperature. The mixed solvent was evaporated under vacuum and placed in a refrigerator before performing DSC measurement. The other reactants were heated on hot plates and cured at 120°C for 1 h, 180°C for 1 h and 240°C for 1 h. Then, cured samples were cooled slowly to room temperature to prevent cracking.

2.4. Preparation of composites

The *N,N'*-bis(5-hydroxy-1-naphthyl)pyromellitic diimide-based epoxy resin and DER 330 were mixed in a 4:1 weight ratio, then mixed with the curing agent DDS in a 1:1 equivalent ratio. The resin system above was dissolved in a solvent mixture of *N,N*-dimethylformamide and methyl isobutyl ketone in a 1:1 volume ratio: 80 wt% solution was obtained for the preparation of composites by pultrusion.

The carbon fiber reinforced composites were prepared with a dragging force of 2000 N, a dragging speed of 2.0–2.5 m/min, mould temperature of 210°C and post-curing temperature of 260°C.

2.5. Characterization

Calorimetric studies were carried out on a Perkin-Elmer DSC-7 under nitrogen atmosphere. Samples (approximately 8 mg) were sealed hermetically in aluminum pans. For non-isothermal DSC runs, the samples were heated from 35 to 300°C at four different rates (5, 10, 15 and 20°C/min) to investigate the dynamic curing procedure. For isothermal cure, the DSC furnace were pre-heated to 150°C and the sample pans were immediately inserted into the furnace, then the samples were heated to the isothermal curing temperature from 185 to 210°C in 5°C increments. At the end of each curing run the samples were quickly cooled to room temperature and the residual heat of reaction ΔH_r was evaluated by reheating from 35 to 300°C at 20°C/min. The total heat ΔH_o evolved during cure is equal to the isothermal heat ΔH_i added to ΔH_r . Dynamic mechanical thermal analysis (DMTA) was carried out with a TA DMA Q800 instrument using 2 mm × 10 mm × 30 mm rectangular samples at a programmed heating rate of 3°C/min from 50 to 300°C at a frequency of 1 Hz under air atmosphere. Moisture absorption was tested as follows: 10 mm × 10 mm × 2 mm rectangular samples were dried under vacuum at 120°C for 24 h until trace water had been expelled, then cooling to room temperature, the samples were weighed and placed in 100°C water for 144 h and weighed again. The limiting oxygen index (LOI) is the minimum fraction of oxygen in a mixture of oxygen and nitrogen which could just support flaming combustion. The LOI tests were performed according to the testing procedure of ISO4589-1984 with test specimen bar of 7–15 cm in length, 6.5 ± 0.5 mm in width and 3.0 ± 0.5 mm in thickness. Ten sample bars suspended vertically were ignited by a Bunsen burner. The flame was removed and the timer was started. The concentration of oxygen was raised if the specimen was extinguished before burning for 5 cm in 3 min. The oxygen content was adjusted until the limiting concentration was determined. Tensile and shear properties were measured on a Zwick Roell Z202 Universal Material Testing Machine according to ASTM D3039 and ASTM D2344, respectively. Thermogravimetric analysis (TGA) was performed using a Perkin-Elmer Pyris 1 thermogravimetric analyzer at a heating rate of 10°C/min under nitrogen and air atmospheres.

3. Results and discussion

3.1. Non-isothermal kinetic analysis with Kissinger's method

Non-isothermal experiments were performed from 35 to 300°C at different heating rates, the kinetic analysis was

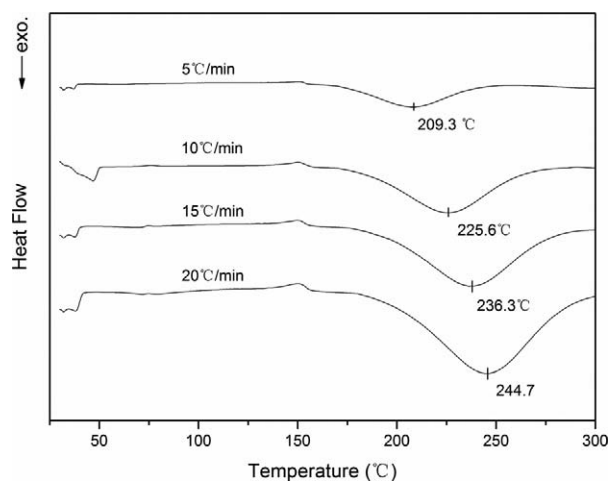


Figure 1. Non-isothermal DSC curves with different heating rate.

Table 1. Dynamic cure reaction parameters.

Heating rate (°C/min)	T_o (°C)	T_p (°C)	ΔH (kJ/mol)	E_a (kJ/mol)
5	177.2	209.3	113.17	
10	182.9	225.6	111.58	73.30
15	183.8	236.3	108.50	
20	185.1	244.7	106.78	

performed using Kissinger's model.^{20,21} According to Kissinger's method, the activation energy can be obtained from the maximum reaction rate at peak exotherm temperature in DSC curves. The relation could be expressed as the following equation:

$$\frac{d[\ln(q/T_p^2)]}{d(1/T_p)} = -\frac{E_a}{R} \quad (1)$$

where T_p is the peak exotherm temperature, q is a constant heating rate, E_a is the activation energy, and R is the gas constant. Therefore, E_a could be calculated from slope of the plot of $\ln(q/T_p^2)$ versus $1/T_p$ without the need of any assumption about the conversion-dependent equation. Figure 1 shows the non-isothermal DSC scans of naphthyl-imide epoxy resin/DDS system with different heating rates.

The dynamic cure reaction parameters are summarized in Table 1.

The Kissinger analysis is based on the relationship between the heating rate and the T_p . The value of E_a and T_p is lower than the other naphthyl-containing epoxy systems⁶ with the same analysis method, even lower than some DGEBA/amine systems. It may be concluded that the incorporation of imide group into the naphthyl-containing backbone could increase the reactivity toward amines.

3.2. Non-isothermal kinetic analysis with AICM

On the basis of the model-free isoconversional methods, changes in the mechanism are associated with changes in the effective activation energy.^{22, 24} These methods used the isoconversional principle considering that the reaction rate at a certain extent of conversion is only a function of temperature. Compared with other isoconversional methods,²⁵ the AICM of Vyazokin et al.^{22,26,27} has the merit of decreasing the systematic error to estimate the activation energy. This method has been successfully applied to study the curing process and other complex reaction system including the cure kinetics of a novel naphthyl/dicyclopentadiene epoxy resin synthesized in our previous work.²⁶ Without assuming a particular form of reaction model, AICM could be used to evaluate activation energy as a function of reaction extent (α). By virtue of the assumption that the reaction model is independent of the heating program, the J -integrals in the range of $\Delta\alpha$ for any given value of α are equal for all experiments, regardless of differences in the heating programs. For a series of n experiments carried out under different temperature programs, $T_i(t)$, the activation energy is determined at any particular value of α by finding E_{α} , which minimizes the function, $\Phi(E_{\alpha})$ ²²

$$\Phi(E_{\alpha}) = \sum_{i=1}^n \sum_{j \neq i}^n \frac{J[E_{\alpha}, T_i(t_{\alpha})]}{J[E_{\alpha}, T_j(t_{\alpha})]} \quad (2)$$

where the subscripts i and j represent ordinal numbers of two experiments performed under different heating programs, $T_i(t)$, and the J integrals

$$J[E_{\alpha}, T_i(t_{\alpha})] = \int_{t_{\alpha-\Delta\alpha}}^{t_{\alpha}} \exp\left[\frac{-E_{\alpha}}{RT_i(t)}\right] dt \quad (3)$$

In Equation (3), α varies from $\Delta\alpha$ to $1 - \Delta\alpha$ with a step $\Delta\alpha = 1/m$, where m is the number of intervals chosen for analysis. Because m is set as 50 in this program, $\Delta\alpha$ equals 0.02. The integrals, J , in Equation (3) are evaluated numerically by using the trapezoid rule, with MATLAB toolboxes. The minimization procedure is repeated for each value of α to find the dependence of the activation energy on the extent of conversion.

Figure 2 shows the variation of effective activation energy with conversion.

In the early curing stages ($\alpha < 0.15$), the activation energy decreased from 74.1 to 62.7 kJ/mol and then remains almost constant. The decrease in the effective activation energy of epoxy curing is likely associated with the rate dependence on viscosity.²⁴ With the increase of temperature, the viscosity of the curing system decreases and diffusion becomes easier, which may facilitate the collision of the monomers in the early curing stage. In the middle curing stages, the activation energy remained the same around 60.1 kJ/mol, so an autocatalytic reaction

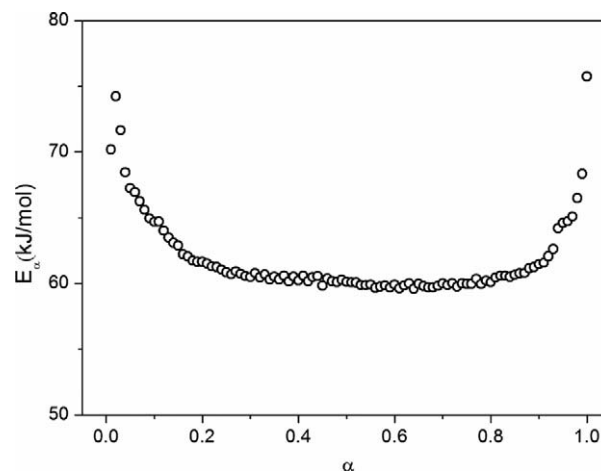


Figure 2. Dependence of the effective activation energy on the extent of conversion.

mechanism gradually appears. The mobility of molecules in the curing system becomes difficult because viscosity is increased in the reaction medium and the size of the reactive molecules is constantly growing. The diffusion control effect is another factor which influences the effective activation energy.²⁶ As temperature rises, the diffusion rate of the curing system increases and makes the effective activation energy decrease. Both of the two competing mechanisms affect the reaction rate simultaneously and the diffusion is a little more predominant. In the final curing stages, a significant increase in effective activation energy was observed. As the reaction sequentially progresses, the high crosslinked network was formed and the polymer chains lose their ability to move one past another. The dramatic decrease in the molecular mobility affects the curing kinetics that becomes controlled by the diffusion of reactants, which leads to a higher activation energy of the curing system.

3.3. Isothermal kinetic analysis with Kamal's model

In general, the n th-order kinetics and autocatalytic kinetics are the two typical reaction mechanisms that describe the thermoset curing reaction. The n th-order kinetics²⁶ and the autocatalytic kinetics model by Kamal¹⁹ could be expressed as in the following equations, respectively,

$$\frac{d\alpha}{dt} = k(T)(1 - \alpha)^n \quad (4)$$

$$\frac{d\alpha}{dt} = (k_1 + k_2\alpha^m)(1 - \alpha)^n \quad (5)$$

where α is the extent of reaction and is calculated from $\alpha = \Delta H_t / \Delta H_o$, the partial area under a DSC curve versus time t , $k(T)$ is the rate constant at temperature T , m and n are the reaction orders, k_1 and k_2 are the specific reaction rate

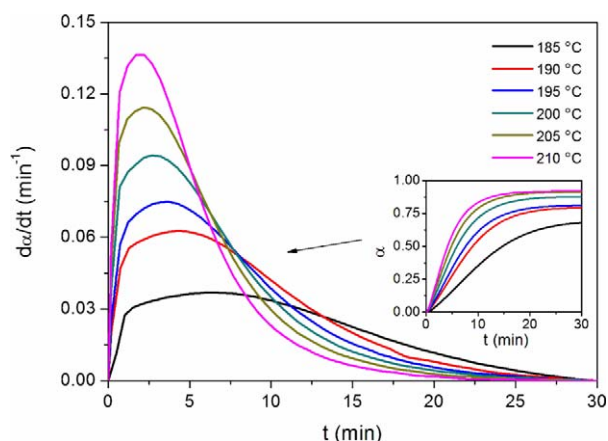


Figure 3. Curing reaction rate $d\alpha/dt$ versus time t at different temperatures.

constants of Kamal model and follow the Arrhenius relationship

$$k_i = A_i \exp(-E_i/RT) \quad (6)$$

Here E_i could be calculated from the slope of the plot of $\ln k_i$ versus T .

For an n th-order kinetics model, the maximum reaction rate will be observed at $t = 0$, and according to the Kamal model, the reaction rate starts from zero initially and attains a maximum value at some intermediate conversion.

Figure 3 shows the rate of curing reaction $d\alpha/dt$ versus time. It was found that the curing reaction rate increased with time during the early curing stage and reached a maximum, so the Kamal model is suitable for this curing process. A genetic algorithm from the MATLAB toolbox was used to compute the parameters from the experimental data.

Figure 4 shows the comparisons between the experimental DSC data and the Kamal model with parameters from Equation (5), the kinetic behavior agrees well in the early and middle curing stages. However, deviations appear in the later curing stage because of the mobility of reactive groups is hindered, and the rate of conversion is controlled by diffusion rather than by kinetic factor.

The differences could be interpreted by free-volume considerations: the free volume of materials decreases with the decrease in temperature and increases in the curing extent; the rate of diffusion of the reactive groups was reduced, resulting in a fall in the curing reaction rate.²⁷ To characterize the onset of the diffusion control effect, a diffusion factor $f(\alpha)$ could be defined as follows:

$$f(\alpha) = \frac{k_e}{k_c} = \frac{1}{1 + \exp[C(\alpha - \alpha_c)]} \quad (7)$$

where k_e is the overall effective rate constant, k_c is the rate constant for chemical kinetics, C is a constant, and α_c is a critical value dependent on curing temperature. The values

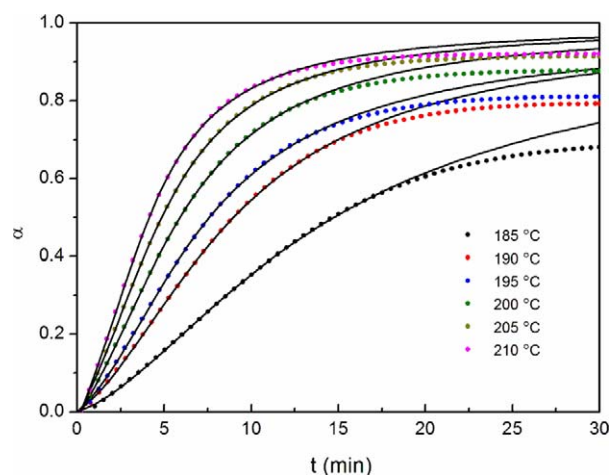


Figure 4. The plots of the conversion α versus time t at different temperatures: (●) experimental data; (—) Kamal's model from Equation (5).

of C and α_c could be obtained by fitting the modified Kamal model as follows:

$$\frac{d\alpha}{dt} = (k_1 + k_2\alpha^m)(1 - \alpha)^n \frac{1}{1 + \exp[C(\alpha - \alpha_c)]} \quad (8)$$

The parameters of $f(\alpha)$ are shown in Table 2.

When the curing reaction is dominated by the kinetic control stage, α is relatively smaller and the value of $f(\alpha)$ approximates unity. As α approaches α_c , $f(\alpha)$ decreases and reaches a value of 0.5 at $\alpha = \alpha_c$, and finally approaches zero as the cure effectively stops. Figure 5 shows a comparison between experimental data with those from Equation (8). The calculated results agree well with the original experimental curves both in the early curing stage and the latter.

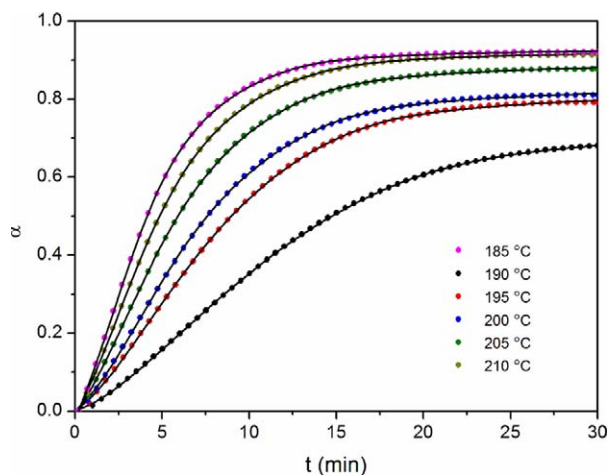
3.4. Isothermal kinetic analysis with AICM

AICM can be also used to analyze the isothermal DSC data. Under isothermal conditions, T_i is held constant, so Equation (3) can be solved analytically. The number of intervals is also set as 50 in this program. The integrals, J , in Equation (3) are evaluated numerically by using the trapezoid rule, with MATLAB toolboxes. The minimization procedure is repeated for each value of α to find the dependence of the activation energy on the extent of conversion. However, the final extent of conversion is lower than 0.9 in isothermal DSC runs, the activation energy on the extent of conversion of 0.02–0.9 could be obtained (Figure 6).

The change in activation energy with the extent of conversion depicted in Figure 6 suggests that the reaction under investigation is a multistep process. In the early curing stage ($\alpha < 0.3$), E_α decreases slightly from 68 to 63 kJ/mol. The high initial value of E_α could be ascribed to the non-autocatalyzed reaction that predominates at the beginning of the process.³⁰ In the middle curing stage

Table 2. Isothermal cure kinetic parameters.

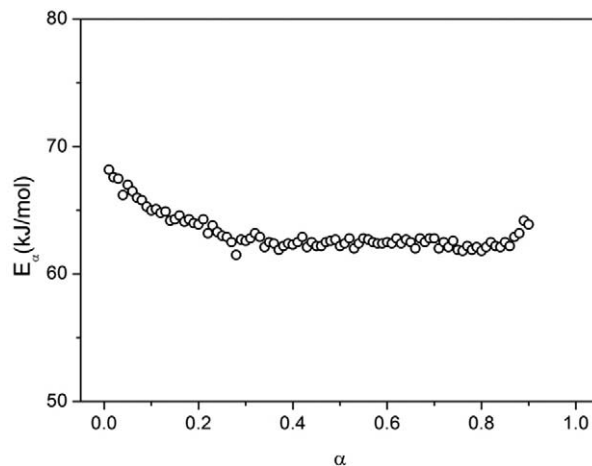
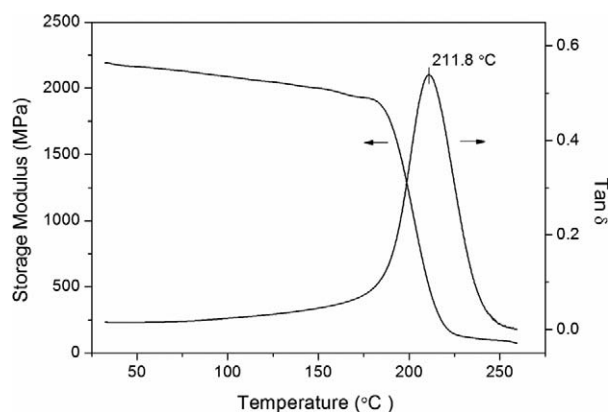
Temperature (°C)	k_1 (s ⁻¹) × 10 ³	k_2 (s ⁻¹) × 10 ²	m	n	C	α_c	E_1 (kJ/mol)	E_2 (kJ/mol)
185	0.202	0.207	0.569	1.874	30.4	0.6499	61.99	45.89
190	0.527	0.390	0.795	1.841	44.7	0.7557		
195	0.642	0.565	0.885	2.030	50.0	0.7774		
200	1.253	0.676	1.106	1.847	57.3	0.8483		
205	1.642	0.950	1.284	1.849	87.6	0.8936		
210	1.977	1.169	1.306	1.870	100.1	0.9007		

**Figure 5.** The plots of the conversion α versus time t at different temperatures: (●) experimental data; (—) autocatalytic model with diffusion factor from Equation (8).

($0.3 < \alpha < 0.8$), E_a almost remains constant and averaged values of activation energy around 63 kJ/mol were obtained that are in good agreement with both isothermal model-fitting kinetic values and non-isothermal AICM results. In the final curing stage ($0.3 < \alpha < 0.9$), E_a increases gradually to 65 kJ/mol, suggesting that samples isothermally cured at temperatures ranging from 185 to 210°C may not reach the conversion at complete vitrification and the curing reaction was mainly controlled by diffusion near the completion of the cure.

3.5. Characteristics of the cured polymer and composites

3.5.1. Dynamic mechanical thermal analyses. Dynamic mechanical observations were performed to analyze the dynamic elastic modulus and occurrence of molecular mobility transitions such as the glass transition temperature.⁶ A small quantity of DGEBA epoxy resin and mixed solvent was added to increase the wetting ability of the naphthyl-imide epoxy resin toward carbon fiber. Figure 7 shows the DMTA scans of the cured epoxy resin. The peak temperature of $\tan\delta$ was taken as the glass transition temperature. The DMTA measurement indicated that the cured polymer had a T_g of 211.8°C, which is slightly lower than a

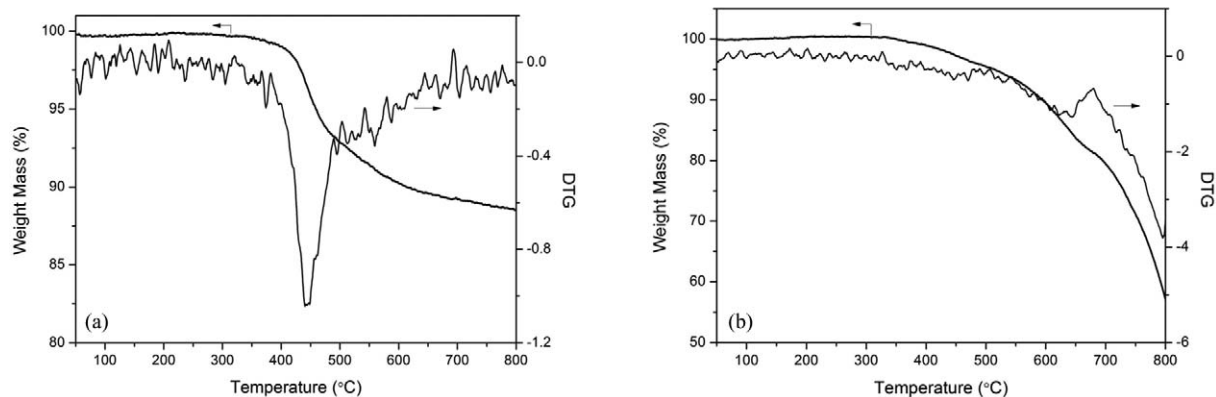
**Figure 6.** Dependence of the activation energy on the extent of conversion from isothermal DSC data by AICM.**Figure 7.** DMTA results of the cured polymer.

pure naphthyl-imide epoxy resin/DDS system,¹⁷ but higher than diglycidyl ether of bisphenol A epoxy resins of 172.9°C,²⁹ and the phenyl-containing epoxy system reported in the literature.^{32,33} The glass transition temperature of the cured polymers could rise by introducing the rigid naphthalene group into the molecular backbone, which could restrain the thermal movements and rotations.

3.5.2. LOI test of the cured epoxy resin. LOI is defined as the minimum fraction of oxygen from the oxygen–nitrogen

Table 3. Tensile and shear properties of the composites.

Temperature	Tensile properties			Shear properties
	Tensile strength (MPa)	Tensile modulus (GPa)	Strain at break (%)	Interlaminar shear strength (MPa)
R.T.	2406	123	1.31	67.9
180°C	2237	107	1.67	60.8

**Figure 8.** Thermogravimetric analysis curves of the carbon fiber reinforced composites: (a) nitrogen atmosphere; (b) air atmosphere.

mixture, which is sufficient to sustain combustion of the specimens after ignition. The value of LOI can be used to evaluate the flame retardant properties of polymers. The cured resin has a LOI of 26.5, which is similar to that of traditional flame retardant diglycidyl ether of tetrabromobisphenol A epoxy resin cured with DDS (LOI = 27) and higher than DGEBA epoxy resin cured with DDS (LOI = 22.5).³⁴ The flame retardant property of the cured resin was slightly enhanced by relatively higher nitrogen content in the cured network.

3.5.3. Moisture absorption. Moisture absorption will reduce the insulation property of the cured polymer. For a high-performance epoxy polymer, it is necessary to decrease the moisture absorption. The moisture absorption was calculated as percentage weight gain:

$$\text{Moisture absorption \%} = (W/W_0 - 1) \times 100\%$$

where W is the weight of sample after dipping in 100°C water for 72 h, W_0 is the weight of sample after placing in a vacuum oven for 24 h. The cured polymer exhibited low moisture absorption of 0.717% and the carbon fiber reinforced composite exhibited a value of 1.082%. The low moisture absorption may be attributed to the hydrophobic nature of naphthyl structure.

3.5.4. Tensile and shear properties of the composites. Table 3 shows the tensile and shear properties of the composites in room temperature and high temperature (180°C). The composites prepared by pultrusion exhibit a tensile strength of 2406 MPa in room temperature and 2237 MPa at 180°C,

illustrating that there is just about 7.02% tensile strength loss at high temperature. Similar results are also found in tensile modulus and shear strength. The high stability of the tensile and shear properties may be attributed to the combination of a rigid naphthyl structure and steady imide linkage in the crosslinked network, which are the necessary conditions for long-term use at high temperature.

3.5.5. Thermogravimetric analysis of the composites. TGA is the most favored technique for rapid evaluation in the thermal stability and degradation behaviors of various polymers. Figure 8(a) and 8(b) is the TGA and its differential curves (DTG) of the carbon fiber reinforced composites. The results indicated that the temperature of 5% degradation of the composite is 421.7°C under nitrogen atmosphere and 478.1°C under air, suggesting that introducing of stable imide structure and naphthyl groups could effectively improve the thermal stability of the composites. However, the rapid weight loss started from 500°C under air atmosphere, the presence of oxygen and carbon fiber results in a complicated decomposition mechanism of the composites and the pyrolysis reaction was activated by the existence of oxygen.¹⁷

4. Conclusions

In summary, a new naphthyl-imide-based epoxy resin was prepared and its curing characteristics with DDS have been investigated. In the initial curing stage during non-isothermal measurements, the activation energy calculated

from AICM is consistent with that obtained from Kissinger's model. Owing to the competitive mechanism of diffusion, the activation energy varies towards the extent of conversion in the latter curing stage. In the isothermal measurement, the curing system shows autocatalytic behavior and was well fitted by Kamal's model extended with a diffusion factor both in kinetically and diffusion controlled stages. The activation energy of k_1 and k_2 was 61.99 kJ/mol and 45.89 kJ/mol, respectively. Furthermore, with the incorporation of rigid naphthyl structure and steady imide linkage, the composites prepared from this resin reveal a high glass transition temperature of 211.8°C and a low percentage loss of 7.02% in tensile strength at 180°C. These pronounced properties make the resin an attractive candidate for circuit packaging materials, advanced composites and other high heat resistant applications.

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