

Effect of Functionalized Magnetite Nanoparticles and Diaminoxanthone on the Curing, Thermal Degradation Kinetic and Corrosion Property of Diglycidyl Ether of Bisphenol A-Based Epoxy Resin

Moslem Mansour Lakouraj*, Ghasem Rahpaima and Ehsan Nazarzadeh Zare

Department of Polymer Chemistry, Faculty of Chemistry, University of Mazandaran, Babolsar, Iran

Abstract To prepare a high-performance epoxy resin with excellent thermal, chemical and corrosion stability, diaminoxanthone (DAX) was used to cure diglycidylether of bisphenol-A (DGEBA)-based epoxy resin and blend of DGEBA with functionalized Fe_3O_4 nanoparticles. Kinetic parameters of curing and thermal degradation of epoxy resin systems were estimated by differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), respectively. The 10% weight loss temperature has been increased from 340 °C to 366 °C and there was an increase in the char yield from 32.6% to 45.3% for the above systems. The corrosion performance of epoxy coated carbon steel was examined by potentiodynamic polarization, along with immersion test in 1.0 mol/L HCl solution. The results showed that epoxy resins cured with DAX had low tendency to corrosion. In addition, the cured epoxy resin containing 10% Fe_3O_4 had higher anticorrosion activity than bare DGEBA system. The results showed that functionalized Fe_3O_4 nanoparticles enhanced char formation and improved the thermal stability as well as anticorrosion activity of the resin.

Keywords: Epoxy resin; Diaminoxanthone; Nanocomposite; Thermal properties; Corrosion stability.

INTRODUCTION

Xanthenes are an excellent category of chemical compounds with a fused polycyclic structure bearing conjugated double bonds, which make the xanthone molecule very stable toward heat and ultra-violet radiation. Indeed, xanthone derivatives are of naturally and synthetically important analogues possessing admirable thermo-oxidative and hydrolytic stability with several biological and pharmacological properties such as anti-inflammatory^[1], antiviral^[2], antifungal^[3], antioxidant^[4], antimicrobial^[5] and antidepressant^[6] activities.

Magnetic supplies are one of the motivations in producing superior materials in the new technology area. Among magnetic materials, magnetite (Fe_3O_4) exists in nature. Investigators have been engaged in various fields such as physics, medicine, biology and material sciences due to its multipurpose characteristics including small size, supermagnetism and low toxicity^[7].

To meet the increasing needs of the rapidly developing field of high technology, the researches for the development of high thermal and corrosive resistance polymers are rising. The chemistry and technology related to epoxy resin because of possessing numerous exciting characteristics, such as low shrinkage, ease of cure and processing, excellent moisture, solvent and chemical resistance, good mechanical and electrical properties and adhesive strength, and ease of modification to make optimal the properties, continue to captivate the researchers.

Epoxy resins are utilized widespread on a large scale for adhesive, lamination, coating, casting applications, and so forth. To assemble some purpose demands, a number of approaches have been used to plan high-

* Corresponding author: Moslem Mansour Lakouraj, E-mail: lakouraj@umz.ac.ir

Received January 9, 2014; Revised February 19, 2014; Accepted February 27, 2014

doi: 10.1007/s10118-014-1535-5

performance epoxy resins, especially to improve their environmental and thermal properties^[8–12].

It has been reported that the incorporation of well-dispersed functionalized nanoparticles such as SiO₂, TiO₂, Fe₃O₄, Al₂O₃ and *etc.* in polymer matrix may effectively enhance the corrosion protection of neat polymer coating due to the increased tortuosity of diffusion pathway of O₂ and H₂O molecules in the matrix. The incorporation of nanoparticles into epoxy resin can significantly improve the mechanical properties^[13], thermal properties^[14], anticorrosion and tailoring of electronic packaging properties^[15].

Epoxy resins because of their excellent adhesion, good mechanical properties and their notable chemical resistance under different aggressive environments, such as wet and high humidity conditions^[16, 17], are one of the most common organic coatings which have been extensively used and studied as anticorrosion coatings to protect metals against versatile corrosion environments. The resistance concerning the different corrosive agents depends on the type of resin as well as on the type and amount of hardener^[18].

Polyxanthenes are a class of high polymers with excellent thermal and chemical resistance^[19]. In continuation of our ongoing work on polyxanthenes^[20] and also in order to access to epoxy resins with anticorrosive activity and high thermal stability, in the present study, we have used 2,7-aminoxanthone as curing agent for epoxy systems to acquire a new type of functional polyxanthenes. For this purpose, at first 2,7-diaminoxanthone was prepared and then used in thermally curing process of neat DGEBA and nanocomposite of DGEBA with magnetic functionalized Fe₃O₄ nanoparticle. The curing and thermal degradation kinetics of this curing system with epoxy resin and its nanocomposite were studied by using differential scanning calorimetry (DSC) analysis and thermogravimetric analysis (TGA), respectively. The water sorption and anticorrosive activity of the fully cured epoxy systems were investigated. The epoxy resin and its nanocomposite were identified by a series of electrochemical measurements such as corrosion potential (E_{corr}), polarization resistance (R_p) and corrosion current (I_{corr}) studied in 1.0 mol/L HCl electrolyte.

EXPERIMENTAL

Materials

The epoxy compound used in the study was a diglycidyl ether of a bisphenol A (DGEBA)-based epoxy, Epidian 5: epoxide equivalent weight (EEW) of 196–208 g/mol epoxide, clear yellow liquid, viscosity (at 25 °C) 25000 MPa·s, provided from Iran Petrochemical Industry. Ferric chloride (FeCl₃·6H₂O), 1, 2-ethylene diamine (ReagentPlus grade), ethylene glycol (anhydrous), sodium acetate (ReagentPlus[®], ≥ 99.0%), and all solvents were purchased from Merck and Fluka Chemical Co, and were used without further purification. Also, xanthone (99%) was provided from Alfa Aesar chemical Co.

Characterization

FTIR was carried out on a Bruker Tensor 27 spectrometer. VSM measurements were performed by using a Vibrating sample magnetometer Daghigh Kavir Corporation-Iran. FESEM was recorded on a Hitachi S4160 instrument. Differential scanning calorimetry (DSC) analysis was performed on a Perkin-Elmer Pyris 6 DSC (Groningen, Netherlands). Thermogravimetric analysis (TGA) was conducted using a TGA-50 analyzer (Shimadzu, Kyoto, Japan) in the temperature range of 50–700 °C under nitrogen atmosphere at a heating rate of 10 K/min. Electrochemical corrosion measurements were performed by a Solatron electrochemical workstation in a conventional three electrode electrochemical cell with a Pt counter electrode and a saturated calomel reference electrode (SCE). The potentiodynamic polarization (PDP) plots (Tafel curves) were obtained in the potential range from –700 mV to + 700 mV (E_{corr} in V versus SCE) at a sweep rate of 2 mV/s.

Preparation of Functionalized Fe₃O₄ Nanoparticles

Functionalized magnetic Fe₃O₄ nanoparticles were prepared according to the already reported method with some modification^[21]. The magnetic functionalized Fe₃O₄ nanoparticles were prepared by the conventional one pot hydrothermal method: 0.400 g (1.48 mmol) of FeCl₃·6H₂O and 0.279 g (3.4 mmol) of sodium acetate were dissolved in 20 mL of ethylene glycol. Then 6.0 mL of ethylenediamine (30.0 mol/L) was added under continuous stirring at 220 °C for 6 h. After completion of the reaction, the solid product was collected by

magnetic filtration and washed several times with deionized water and absolute ethanol. The final product was dried in a vacuum oven at 100 °C for 6 h.

Preparation of Curing Agent

2,7-Dinitro and 2,7-diaminoxanthone were prepared according to our published articles^[20].

Sample Preparation

The stoichiometric amount of DAX (28.25 phr) was dissolved in DGEBA by stirring at room temperature. Epoxy-nanocomposite was prepared as follow: DAX was dissolved in DGEBA first and then amino-functionalized Fe₃O₄ (10% of total weight of DGEBA and DAX) was mixed thoroughly in DGEBA/DAX system by vigorous stirring for sufficient time (about 15 min) to give a homogeneous viscous mixture. Bulk samples of 1000 mg were prepared and kept in a refrigerator prior to the measurements. About 10 mg in size samples were used for DSC measurements. For the TGA experiment, epoxy resin and stoichiometric amount of DAX was carefully and homogeneously mixed, and then 10% Fe₃O₄ nanoparticles was added. The mixtures were safely introduced into a cylindrical frame and finally the curing reaction conducted according to the following schedule which contains two stages: (1) curing the compositions in a vacuum oven at 70 °C for 2 h, and (2) post curing of the samples at 120 °C for 45 min.

Water Sorption

Two examination methods were investigated for water absorption capacity of dried cured epoxy resin systems (50 mm diameter and ~3.0 mm thickness). Method I: epoxy polymers were immersed in 30 mL water at 25 °C for 24 h, and Method II: epoxy polymers immersed in water at 100 °C for 30 min, removed from the water and weighed on a balance accurate to 0.01 mg after the liquid water on their surface blotted away and its weight difference was definite before and after immersion.

RESULT AND DISCUSSION

Characterization of Functionalized Fe₃O₄ Nanoparticles and Nanocomposites

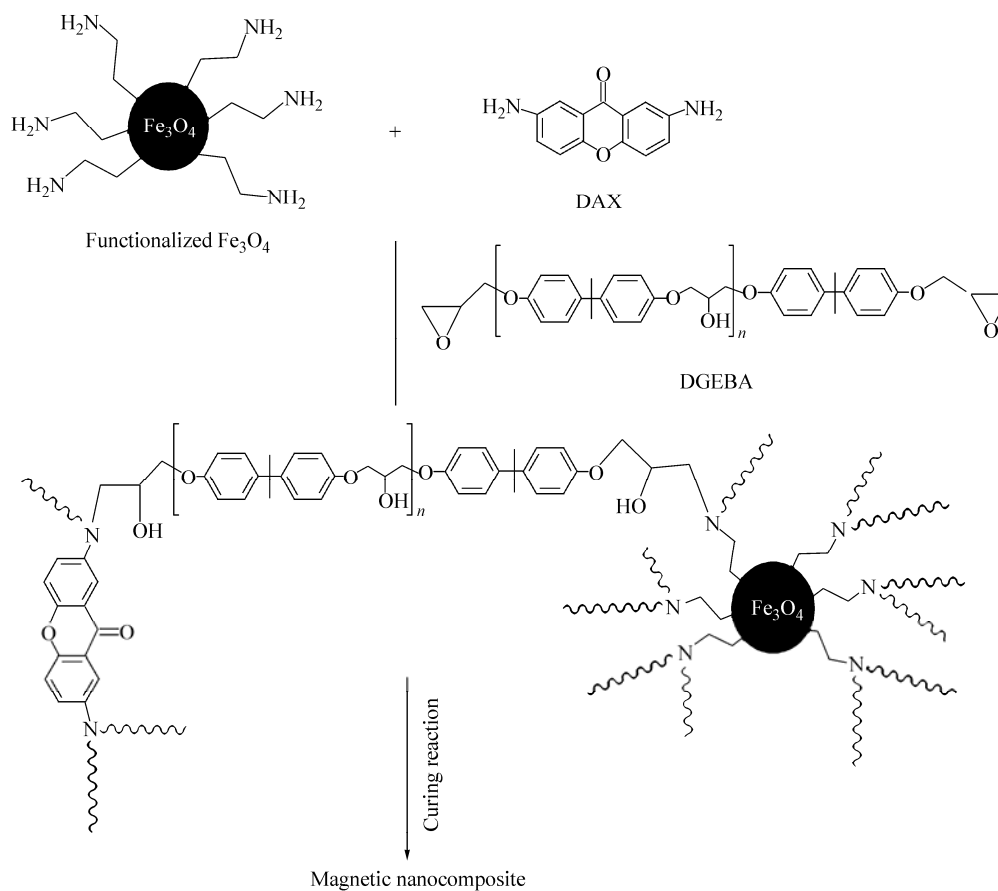
Due to poor compatibility of the organic matrix and inorganic nanoparticles, it is necessary to improve compatibility between the nanoparticles and the polymer matrix during the preparation of hybrid (or nanocomposite) materials^[15]. For this purpose, functionalized magnetic Fe₃O₄ nanoparticles were prepared by the conventional one pot hydrothermal method. Functionalized nanoparticles are dispersed well in the epoxy materials due to covalent bond formation between the surface amino groups on nanoparticles with epoxy function of resin (Scheme 1).

The barrier property of epoxy matrix versus oxygen and water could be increased by introducing the functionalized nanoparticles in polymer matrix and therefore, further improve the anticorrosion properties of the polymer.

Figure 1(a) (SEM image) shows that Fe₃O₄ nanoparticles consist of well dispersed spheres. Also the SEM image of the superparamagnetic nanocomposite displays relatively uniform dispersion of nanospheres in epoxy matrices (Fig. 1b). Figure 1(c) shows the XRD patterns of these nanoparticles. The strong and sharp peaks reveal that Fe₃O₄ nanoparticles are well crystallized. No peaks from other phases are detected, indicating the high purity of the products. Their particle sizes were estimated to be in the range of 20–30 nm regarding Debye-Scherrer equation^[22].

$$D = k\lambda / (FW \cos \theta) \quad (1)$$

where D is diameter of particles, k is the shape factor of the average particle (expected to be 0.94), λ is the wavelength (usually 0.15418 nm), θ is the Bragg's angle and FW is the full width at half maximum.



Scheme 1 Synthetic pathway for preparation of DGEBA/DAX/ Fe_3O_4 magnetic nanocomposite

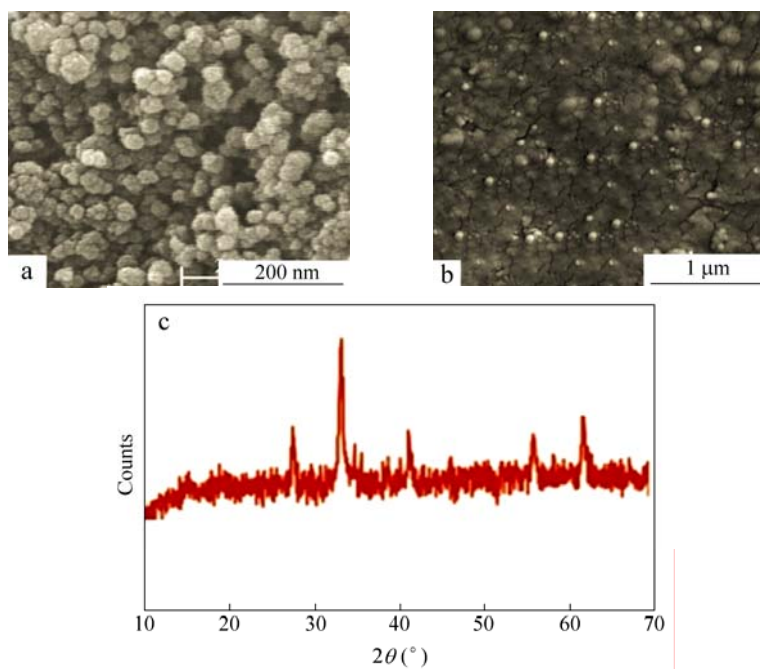


Fig. 1 (a) SEM image of Fe_3O_4 , (b) SEM image of epoxy nanocomposite and (c) XRD pattern of Fe_3O_4

Curing of DGEBA with DAX

The curing rate of epoxy resin depends on the structure and reactivity of the curing agent. The onset of the curing exotherm depends on the nucleophilicity of the amino groups. Figure 2 shows dynamic DSC curves for DGEBA cured with stoichiometric amount of DAX at four different heating rates. All the curves show only one exothermic peak regardless of the heating rate. Also with increasing the heating rate, the exothermic peaks (T_p) shifted towards higher temperatures (from 152 °C to 184 °C). As can be seen in these figures, as the heating rate was increased from 5 K/min to 20 K/min the exothermic peak was shifted to higher temperatures. Faster heating rates gave the sample less time to cure, and the exothermic peak shifted toward higher temperatures.

Figure 3 shows the dynamic DSC thermogram for the reaction of DGEBA with Fe_3O_4 at the heating rate of 10 K/min. The exothermic peak shows that functionalized magnetic Fe_3O_4 nanoparticle is capable to react with DGEBA and T_p appears at 127 °C.

Figure 4 shows dynamic DSC curves for DGEBA cured with stoichiometric amount of DAX in the presence of 10% of Fe_3O_4 at four different heating rates. DSC thermograms in Fig. 4 show two different size exothermic peaks; a small peak associated to the cure reaction of DGEBA with amino groups of Fe_3O_4 in the temperature range of 115–147 °C, as shown in Fig. 3, and a large one in the temperature range of 165–194 °C due to the polymerization reaction of DGEBA with DAX, as shown in Fig. 2.

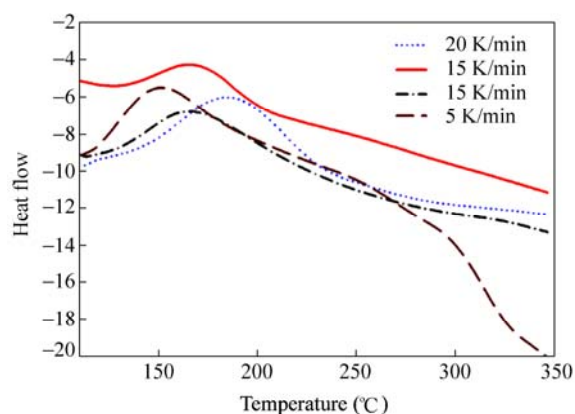


Fig. 2 Typical dynamic DSC thermograms of DGEBA/DAX

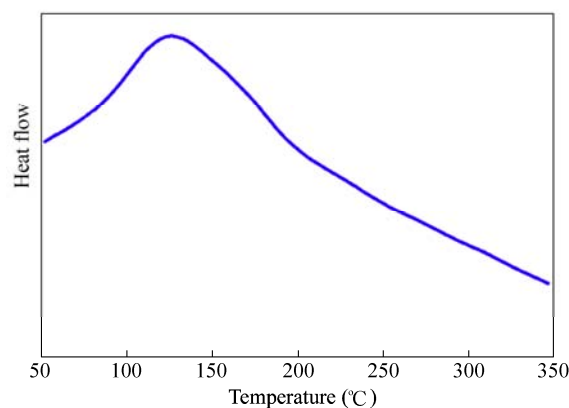


Fig. 3 Typical dynamic DSC thermogram of DGEBA/ Fe_3O_4

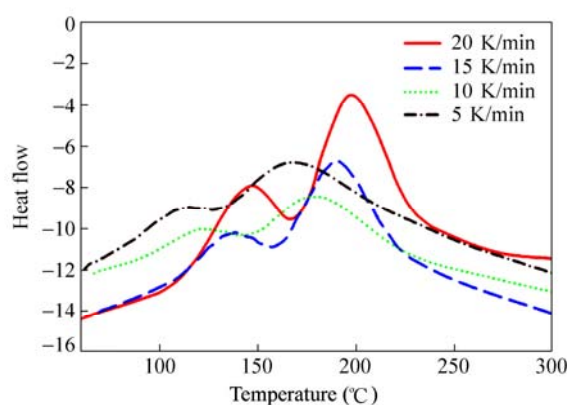


Fig. 4 Typical dynamic DSC thermograms of DGEBA/DAX/ Fe_3O_4

Table 1 presents all the data extracted from the exothermic peak of curing DGEBA with DAX. The exothermic peaks were ascribed to the production of heat throughout the cure reaction.

Table 1. DSC scanning data for the curing of DGEBA at different heating rates

Curing system	β (K/min)	T_p (K)	$1/T_p \times 10^3$ (K ⁻¹)	$\ln\beta$	$-\ln(\beta/T_p^2)$
DGEBA/DAX	5	425	2.35	1.60	10.49
	10	435	2.30	2.30	9.84
	15	441	2.27	2.70	9.47
	20	457	2.19	2.99	9.25
DGEBA/DAX/Fe ₃ O ₄	5	439	2.27	1.60	10.55
	10	450	2.22	2.30	9.91
	15	460	2.17	2.70	9.55
	20	468	2.13	2.99	9.30

The kinetic parameters of curing reaction can be acquired from two multiple-heating rate methods that presented by Kissinger^[23] and Ozawa-Flynn-Wall^[24] Eqs. (2) and (3), respectively:

$$\ln(\beta/T_p) = \ln(AR/E_a) - E_a/RT_p \quad (2)$$

$$\ln(\beta) = \text{const.} - 1.052E_a/RT_p \quad (3)$$

where β is the heating rate, T_p is the peak temperature at different heating rates, E_a is the activation energy, and A is the frequency factor. The dynamic DSC data in Table 1, the temperature at which the instant conversion rate was maximum (T_p) and the heating rate (β) were used for calculation of kinetic parameters by using Kissinger method, Eq. (2), and Ozawa-Flynn-Wall method, Eq. (3).

The E_a values were calculated from the slope of linear plots and the pre-exponential factors from the intersect, and these values are listed in Table 2. The data of fourth and fifth columns in Table 1 were also inserted into the Ozawa-Flynn-Wall equation and plot of $\ln(\beta)$ versus $(1/T_p) \times 1000$ gave straight lines, with a slope of $1.052E_a/R$. The calculated values of E_a are given in Table 2.

Table 2. Values of kinetic parameters for cure reaction of epoxy systems

Curing system	E_a (kJ/mol) ^a	E_a (kJ/mol) ^b	A (min ⁻¹)	k (min ⁻¹)
DGEBA/DAX	61.63	65.56	9.10×10^6	0.63
DGEBA/DAX/10%Fe ₃ O ₄	77.17	73.97	1.54×10^8	0.40

^a Ozawa's method; ^b Kissinger's method

The E_a values for DGEBA/DAX/Fe₃O₄ system as shown in Table 2 are higher than those obtained for DGEBA/DAX system. The increase of E_a in the cure reaction of DGEBA with DAX can be due to the fact that reaction between DGEBA with Fe₃O₄ produces higher molecular weight oligomers with reduced molecular mobility. This makes the next reaction which is between epoxide and amine functional groups more difficult. To compare the cure rate for the two systems, A and E_a values were introduced to the following Arrhenius equation to calculate rate constants at a selected temperature:

$$k = A \exp(-E_a/RT) \quad (4)$$

where k is the rate constant, and T is a selected temperature (450 K). The calculated rate constants for the two systems are shown in Table 2. This also shows that the rate of cure reaction of DGEBA with DAX in the presence of Fe₃O₄ decreases to some extent.

Thermogravimetric Analysis

TGA plans of the cured epoxy samples supply their thermal stability and thermal degradation behaviors. Figure 5 shows TGA curves of the amino-functionalized Fe₃O₄ nanoparticles, cured DGEBA/DAX and DGEBA/DAX/10%Fe₃O₄ systems under nitrogen atmosphere. The relative thermal stability of the cured samples was compared by noting the initial decomposition temperature (IDT), the 10% weight loss temperature (T_{10}), the temperature of maximum rate of weight loss (T_{max}), and the percent of char yield (%C.Y.). Figure 5 shows that the overall weight loss of functionalized Fe₃O₄ is 4.8%. IDT for the cured sample of DGEBA/DAX is about

311 °C and increased to about 333 °C when sample contained 10% of Fe_3O_4 . IDT indicates the apparent thermal stability of the epoxy resins, *i.e.*, the failure temperatures of the resins in processing and moulding. In TGA thermogram of DGEBA/DAX/ Fe_3O_4 cured system, no changes in mass were recorded up to 333 °C. This result, which agrees with the fact that there was no notable mass loss in the thermogravimetric investigation before 333 °C, reveals that the resin is thermally stable below 333 °C. Thermostable solid residue or char yield is 32.6% and 45.3% for DGEBA/DAX and DGEBA/DAX/10% Fe_3O_4 systems, respectively. Therefore, incorporation of Fe_3O_4 in the cured sample of DGEBA/DAX system induces significant effect on the thermal stability of the product. This improvement is a result of the formation of stable and higher amount of solid residue in thermal degradation of DGEBA/DAX/ Fe_3O_4 system in comparison with DGEBA/DAX.

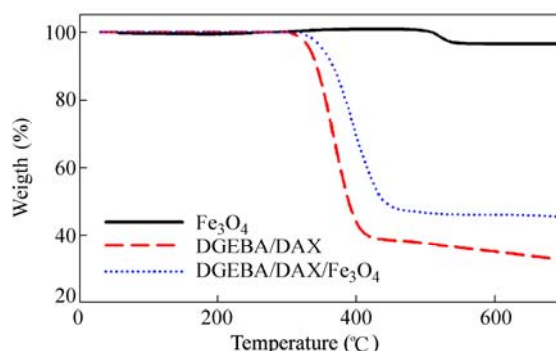


Fig. 5 TGA curves of cured epoxy resins

As the pyrolysis being the first step in the combustion process of polymers, one may expect a relationship between LOI and pyrolysis parameters *i.e.* char yield. It is well expected that the quantity of char yield after pyrolysis depends not only on the elemental content but also on the structure of cured resins.

The char yield can be used as criteria for evaluation of limiting oxygen index (LOI) of the cured halogen-free resins in accordance with Van Krevelen and Hoftyzer, Eq. (5)^[25]

$$\text{LOI} = 17.5 + 0.4 \text{ C.Y.} \quad (5)$$

where C.Y. is char yield. The calculated values of the LOI according to the above equation are given in Table 3. Sample of DGEBA/DAX/10% Fe_3O_4 has a value of 35.62 for LOI which is higher than 30.54 obtained for DGEBA/DAX. On the basis of LOI values, these materials can be classified as self-extinguishing resins.

Calculation of E_a for decomposition of the cured epoxy resin can be carried out from the data of TGA curves, through the integral method based on the Horowitz-Metzger^[26] and Broido^[27] equations:

$$\ln[\ln(1-\alpha)^{-1}] = E_a \theta / RT_{\text{Max}}^2 \quad (6)$$

$$\ln[\ln(1-\alpha)^{-1}] = -E_a / RT_{\text{Max}} \quad (7)$$

where α is the decomposition ratio, θ is the difference between T and T_{max} , T_{max} is the temperature of maximum rate weight loss, and R is the ideal gas constant. E_a based on Horowitz-Metzger equation is given by the straight line corresponding to the plot of $\ln[\ln(1-\alpha)^{-1}]$ versus θ . The plots of $\ln[\ln(1-\alpha)^{-1}]$ versus θ are shown in Fig. 6.

Also, E_a based on Broido equation is given by the straight line corresponding to the plot of $\ln[\ln(1-\alpha)^{-1}]$ versus $(1/T) \times 1000$ as given in Fig. 7.

The E_a values of both systems were calculated from the slope of the straight lines, and the values are listed in Table 3. Thermogravimetric analysis results showed that both cured epoxy systems have good thermal stability. The E_a values of thermal degradation of DGEBA/DAX/10% Fe_3O_4 are higher than those of DGEBA/DAX systems; the higher values of E_a indicate the higher thermal stability of DGEBA/DAX/10% Fe_3O_4 system which can be attributed to the formation of stable and higher char yield. The char yields at 700 °C increased from 32.6% to 45.3% with the addition of Fe_3O_4 to the curing mixture of DGEBA/DAX system. The

relatively higher char yield of epoxy systems can be attributed to the presence of very stable xanthone molecule with an aromatic fused ring structure.

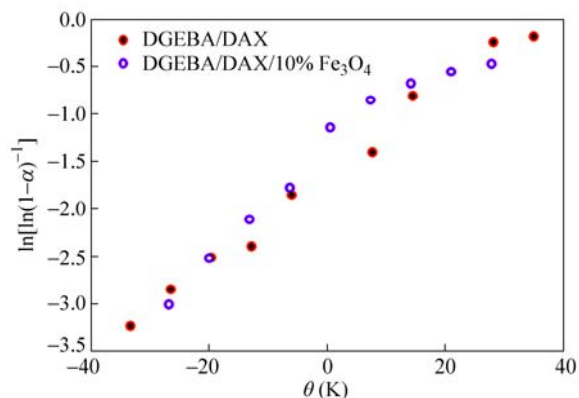


Fig. 6 Horowitz-Metzger plot for epoxy resin systems

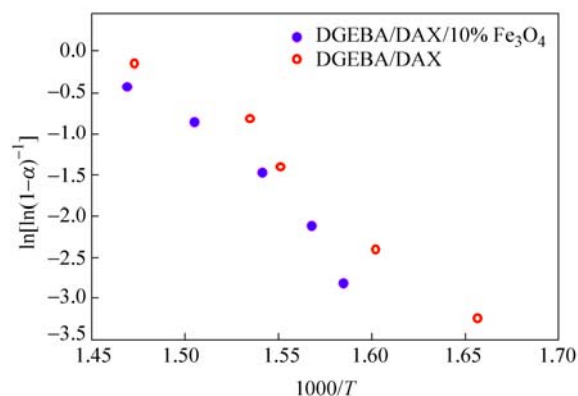


Fig. 7 Brodido plot for epoxy resin systems

Table 3. LOI and E_a values of the thermal degradation of cured epoxy resin

Cured systems	E_a (kJ/mol) ^a	E_a (kJ/mol) ^b	LOI ^c
DGEBA/DAX	156.53	146.33	30.54
DGEBA/DAX/Fe ₃ O ₄	174.06	166.16	35.62

^a Horowitz-metzger's Method; ^b Brodido's Method; ^c Limiting oxygen index

VSM Analysis

The magnetic property of Fe₃O₄ studied with VSM was slightly modified upon epoxy resin coating (see Fig. 8). Though typical superparamagnetic behaviors were observed for both Fe₃O₄ and DGEBA/DAX/10%Fe₃O₄, the saturation magnetization ($M_s = 50$ emu/g) for Fe₃O₄ was slightly reduced to 10.3 emu/g for DGEBA/DAX/Fe₃O₄ due to the increase of diamagnetic epoxy resin on magnetic core.

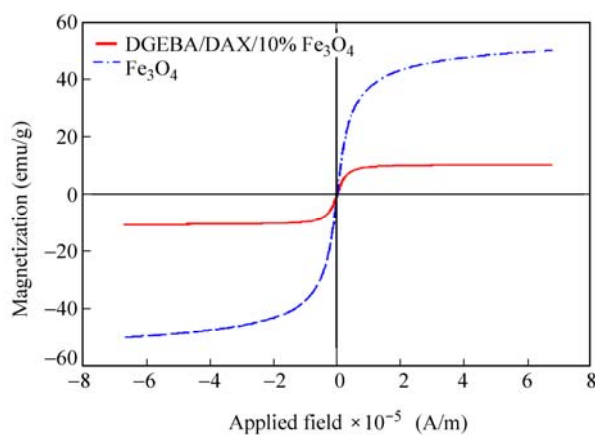


Fig. 8 Magnetization curves of Fe₃O₄ and its nanocomposite

Water Sorption

Because the epoxy resins are hydrophilic, they absorb water from environment. The absorbed water deteriorates the thermal and mechanical properties of the epoxy systems, furthermore begin corrosion of the substrate metal, delaminate the coating and destroy the adhesion between the binder and the enhanced materials. Therefore, water sorption behavior of the epoxy resin became an attractive subject in both macromolecular science and engineering.

According to literature^[28], traditionally two methods were used for the water absorption measurement of epoxy samples (50 mm in diameter and 3.10 mm thick); at 25 °C for 24 h and at 100 °C for 30 min. As can be seen in Table 4, DGEBA/DAX/10%Fe₃O₄ showed lower percent of water absorption compared to the water absorption of DGEBA/DAX. Introduction of Fe₃O₄ nanoparticles in epoxy matrix could reduce the penetration of water in composite due to increase tortuosity of diffusion pathway of O₂ and H₂O molecules in the matrix^[29].

Table 4. Water absorption data of cured epoxy resin

Cured systems	Method 1 (%)	Method 2 (%)
DGEBA/DAX	0.47	0.60
DGEBA/DAX/Fe ₃ O ₄	0.30	0.44

Potentiodynamic Measurements

The electrochemical corrosion measurements of DGEBA/DAX and DGEBA/DAX/Fe₃O₄ coated stainless steel in 1.0 mol/L HCl aqueous solution was determined from a series of electrochemical parameter measurements. Tafel plots of all cases including bare stainless steel; DGEBA/DAX, DGEBA/DAX/10% Fe₃O₄, are shown in Fig. 9. The corrosion potential for both epoxy samples is more positive than that observed in the case of bare metal.

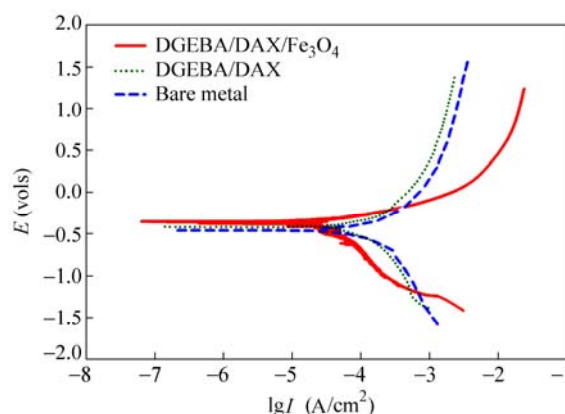


Fig. 9 Polarization behaviors of bare metal and epoxy coatings

Firstly, the corrosion potential (E_{corr}), polarization resistance (R_p) and corrosion current (I_{corr}) of DGEBA/DAX and its nanocomposite coatings on stainless steel show high corrosion resistance, as shown in Table 5. Furthermore, the stainless steel coated with DGEBA/DAX/10%Fe₃O₄ nanocomposite coatings showed significantly higher values of R_p , and lower values of E_{corr} , and I_{corr} compared to that of coated stainless steel without magnetic nanoparticles. The most anodic value of E_{corr} indicates that the nanocomposite coated stainless steel should have the highest corrosion protection. On the other hand, the polarization resistances, R_p , were evaluated from the Tafel plots, according to the Stearn-Geary equation^[30],

$$R_p = (b_a b_c) / 2.303(b_a + b_c) I_{\text{corr}} \quad (8)$$

where I_{corr} , b_a and b_c are the corrosion current density, anodic Tafel slope and cathodic Tafel slope, respectively. The bare stainless steel has the most negative E_{corr} value (−0.461 V) in comparison to neat epoxy and Fe₃O₄-epoxy nanocomposite coated samples (−0.420 V and −0.379 V, respectively), which implies that epoxy samples are noble towards electrochemical corrosion compared to the bare stainless steel. Results revealed that both epoxy samples have higher polarization resistance (R_p) values in 1.0 mol/L HCl electrolyte than bare stainless steel metal, also the 10% Fe₃O₄-epoxy sample shows an R_p value of 2.598 MΩ·cm² which is 1.57 times the R_p of neat epoxy. The electro-chemical parameters (anodic Tafel slope (b_a), cathodic Tafel slope (b_c), I_{corr} , E_{corr} and R_p) are summarized in Table 5.

The protection efficiency ($\%P_{EF}$) values were estimated using the following equation^[31]:

$$\%P_{EF} = 100 \times [I_{corr}(\text{uncoated}) - I_{corr}(\text{coated})] / I_{corr}(\text{uncoated}) \quad (9)$$

Table 5. Potentiodynamic polarization data for bare metal and epoxy coatings

Sample coating	R_p (M Ω)	I_{corr}	E_{corr}	$\%P_{EE}$ (%)
Stainless steel	0.869	5.32×10^{-5}	0.461	—
DGEBA/DAX	1.895	2.34×10^{-5}	0.420	56.01
DGEBA/DAX/Fe ₃ O ₄	2.598	8.77×10^{-6}	0.379	83.51

Thus we proposed that the epoxy systems in the form of coating display an effective enhanced corrosion protection. Fe₃O₄ nanoparticles could act as effective hinder to enhance the oxygen barrier property, therefore, DGEBA/DAX/10%Fe₃O₄ showed better anticorrosion activity than DGEBA/DAX based on a series of electrochemical standard corrosion measurements.

CONCLUSIONS

A high-performance epoxy resin with excellent thermal, chemical and corrosion stability was successfully prepared by using diaminoxanthone as curing agent to cure diglycidylether of bisphenol-A (DGEBA)-based epoxy resin and blend of DGEBA with functionalized Fe₃O₄ nanoparticle. Kinetic parameters of curing and thermal degradation of epoxy resin systems were estimated by differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), respectively. Thermogravimetric analyses showed that both epoxy systems cured with 2,7-diaminoxanthone have good thermal stability. The higher E_a values of thermal degradation and char yields of DGEBA/DAX/10%Fe₃O₄ than DGEBA/DAX systems indicate the higher thermal stability of DGEBA/DAX/10%Fe₃O₄ system. The relatively higher char yield of epoxy systems can be attributed to the presence of very stable xanthone molecules with a fused aromatic ring structure. The presence of Fe₃O₄ in the cured sample of DGEBA/DAX system induced significant effect on the thermal stability of the product: the IDT increased from 311 °C to 333 °C and the char yield increased from 32.6% to 45.3%. This improvement is as a result of the formation of stable and higher amount of solid residue in thermal degradation of DGEBA/DAX/10%Fe₃O₄ system in comparison with DGEBA/DAX system. The results of potentiodynamic polarization showed that epoxy resins coated stainless steel have good anticorrosion activity, and also epoxy resin with 10% Fe₃O₄ displayed excellent anticorrosion activity than the epoxy coated one without magnetic nanoparticle. These nanocomposite coatings show the outstanding corrosion inhibition and promising anticorrosion coating materials in various applied fields. The incorporation of functionalized magnetic Fe₃O₄ nanoparticles in the curing mixtures increased the thermal stability, reduced water adsorption, and also enhanced the corrosion protection properties of the cured samples.

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