

# Evidence for Kinetic Inhomogeneity in the Curing of Epoxy Using the Near-Infrared Multispectral Imaging Technique

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**The kinetics of curing of an epoxy resin by amine was studied using a near-infrared (NIR) multispectral imaging spectrometer. This imaging spectrometer is capable of sensitively and rapidly recording NIR spectral images of a sample because it was constructed with an acousto-optic tunable filter and an InGaAs focal plane array NIR camera. The high sensitivity and fast scanning ability of the spectrometer make it suitable for kinetic determination of fast reactions. Additionally, it has features that conventional NIR spectrometers cannot offer, namely, its ability to provide kinetic information at different positions within a sample. Furthermore, the high spatial resolution and sensitivity of the InGaAs camera make it possible to determine the kinetics from data collected by a single pixel in the camera. The kinetics of curing of epoxy by amine, determined by this multispectral imaging instrument, show that the reaction rates within the sample are very inhomogeneous. Because of this kinetic inhomogeneity, differences in the degrees of cure at different positions within the sample can be as high as 37% when data from only a single pixel were used for calculation. The inhomogeneity was not observed if an average of a large number of pixels were used.**

The near-infrared (NIR) technique has been used extensively in recent years for qualitative and quantitative analysis of polymers.<sup>1–4</sup> The technique has been used for the determination of chemical analysis of individual polymers, the chemical compositions of copolymers, and the kinetics of polymeric reactions.<sup>1–6</sup> For example, it was demonstrated recently, that the kinetics of the cure reaction of epoxy by amine can be determined by the NIR technique.<sup>1–6</sup> Such application clearly demonstrates the potential and utilization of the NIR method. It is, however, important to realize that the analysis of polymers by the NIR method is still in the early stage of the development and that care must be taken to avoid possible errors. The concerns are due to the nature of the polymers and NIR instrument used for measure-

ments. Specifically, polymeric samples are known to be chemically inhomogeneous, and because of the chemical inhomogeneity, rates of a polymeric reaction may be different at different positions in a sample. As a consequence, the polymeric end product may not be chemically homogeneous. Since chemical and physical properties of polymers depend on their chemical compositions, the presence of chemical inhomogeneity will have pronounced effects on their properties. It is, therefore, important that the rate of a polymeric reaction be measured at different positions in a polymer sample in order to determine the presence of any kinetic inhomogeneity. Unfortunately, to date, NIR-based kinetic methods rely on the use of NIR spectrometers equipped with single-channel NIR detectors.<sup>1–4</sup> As such, it has not been possible to simultaneously determine the kinetics of reaction at different positions in a polymer sample. A NIR multispectral imaging spectrometer is needed for such a purpose.

A multispectral imaging spectrometer is an instrument that can simultaneously record spectral and spatial information of a sample. Chemical homogeneity of the sample can be elucidated from recorded images. In these instruments, the spatial distribution of the sample is obtained by a camera, and the spectral information is gained by scanning a dispersive element.<sup>7–15</sup> To be used for kinetic determination, the instrument must be able to sensitively and rapidly record spectral images of a sample. These requirements can be satisfactorily met with the instrument recently developed in our laboratory.<sup>16</sup> In this instrument, an acousto-optic tunable filter (AOTF) is used for spectral scanning and an InGaAs camera for recording NIR images.<sup>16</sup> AOTF is an electronic tunable filter based on the diffraction of light by an acoustic wave in an anisotropic medium. It has rapid scanning

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ability, high diffraction efficiency, wide spectral tuning range, and high resolution.<sup>17,18</sup> Because of these advantages, the multispectral imaging instrument based on an AOTF will have rapid scanning ability. The high sensitivity of the instrument stems from the InGaAs camera, which has the highest sensitivity in the NIR region among cameras currently available (e.g., InSb and HgCdTe cameras). In fact, we were able to use this camera to determine the chemical inhomogeneity of ethylene/vinyl acetate copolymers.<sup>16</sup>

The information presented is indeed provocative and clearly indicates that it is possible to use the AOTF-based multispectral imaging instrument equipped with an InGaAs camera to measure the kinetics of cure reaction of epoxy by amine and to determine the presence of any kinetic inhomogeneity in the sample. Preliminary results of such study are reported in this paper.

## EXPERIMENTAL SECTION

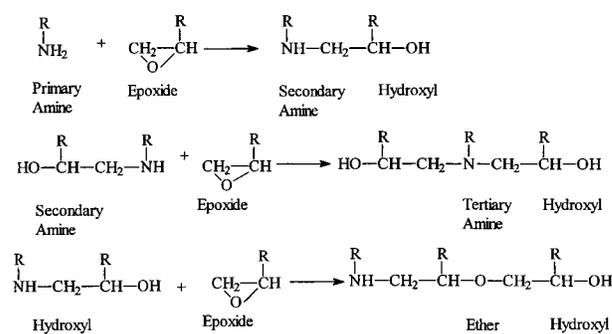
The multispectral imaging instrument used in this study is similar to that used in our previous experiments.<sup>16</sup> Essentially, light from a 250-W halogen tungsten lamp was dispersed by a noncollinear TeO<sub>2</sub> acousto-optic tunable filter and detected by an InGaAs focal plane array camera. Two different InGaAs cameras were used. A majority of the work including the kinetic measurements was obtained with a 128 × 128 pixel, 8-bit InGaAs camera (Sensors Unlimited model SU18-1.7RT/RS170). Inhomogeneity measurements were performed with the 320 × 240 pixel, 10-bit InGaAs camera (Sensor Unlimited model SU 320-1.7RT-D/RS 170).

The epoxy resin, poly(bisphenol A-co-epichlorohydrin) glycidyl end capped, and the amine hardener (i.e., diethylenetriamine) were purchased from Aldrich Chemicals and used as received. The epoxy-amine cure reaction was initiated by vigorously mixing the two compounds for 5 min with a glass rod in a beaker in stoichiometric proportion; namely, the concentration of epoxy was twice the concentration of amine. This ratio is known to produce a 3D network during the cure reaction.<sup>1,4,19,20</sup> The mixture was then introduced to a homemade cell which consists of an aluminum frame with two glass windows separated by a 3-mm-thick rubber frame spacer. The cell was placed in a homemade cell holder equipped with a thermal coupler, a heater, and a temperature controller for the recording, controlling, and maintaining the temperature of the cell.

## RESULTS AND DISCUSSION

**NIR Spectra of the Epoxy-Amine Network from 1000 to 1700 nm.** *Spectral and Timing Characteristics of the NIR Multispectral Imaging Instrument.* Epoxy is known to be cured by amine. The cure reaction between poly(bisphenol A-co-epichlorohydrin) glycidyl end capped and diethylenetriamine is given in Scheme 1. Such a cure reaction was previously studied using the near-infrared technique.<sup>1-4,19-23</sup> In almost all of these studies, NIR spectra were measured in the region from 1600 to 2500 nm. The InGaAs cameras (the 126 × 126 camera as well as the 320 × 240 camera) used in this work are sensitive only in the region from

Scheme 1



1000 to 1700 nm. As a consequence, the initial part of this study was designed to demonstrate that the NIR region from 1000 to 1700 nm can be as effective as the longer wavelength region for the kinetic determinations of the cure of epoxy by amine.

Images of a mixture of epoxy and amine at 25 °C were recorded by the InGaAs camera for each wavelength from 1000 to 1700 nm at 5-nm interval (by scanning the AOTF). The scanning speed of the AOTF is the speed of the acoustic wave in the crystal, which is on the order of microseconds. However, the rate at which an image is recorded by this NIR imaging instrument is much slower than the scanning speed of the AOTF. This is because of the additional time required by other components of the instrument, including the camera (time for exposure and for recording the image) and the frame grabber (to grab the image and to transfer it to the computer). Specifically, the exposure time (or the integration time) of the InGaAs camera is 16 ms. When the time to grab the picture, to transfer, and to store the picture in the computer is added to this exposure, the total time it takes to record one picture is about 100 ms. The total time to record the whole set of 141 pictures (for the whole region from 1000 to 1700 nm at 5-nm interval) is, therefore, 14.1 s. This 141-picture set was recorded every 10 min for the first hour of the reaction and then every 15 min for the rest of the reaction for a total time of 8 h (for reactions at higher temperatures, e.g., 55 °C, because of larger rate constants the set of pictures was recorded every 5 min). From these images, NIR absorption spectra of the epoxy-amine mixture at different times can be determined.

*Assignment of NIR Absorption Bands.* Shown in Figure 1 are the NIR spectra of the sample at different times (from 0 to 8 h). As illustrated, there are several bands. The band that initially centered at 1527 nm can be attributed to the overtones of the primary and secondary amines. Primary aliphatic amines are known to have two absorption bands at 1525 and 1543 nm, whereas secondary amine exhibits only a single absorption band at 1543 nm. As illustrated in Scheme 1, during the cure, primary amines are consumed first to form secondary amine. As a consequence, the intensity of the primary band at 1527 nm not only decreases but also shifts toward longer wavelength (to secondary amine). The much smaller band at 1040 nm, which also decreases as the reaction proceeds, is another overtone from the same transition.

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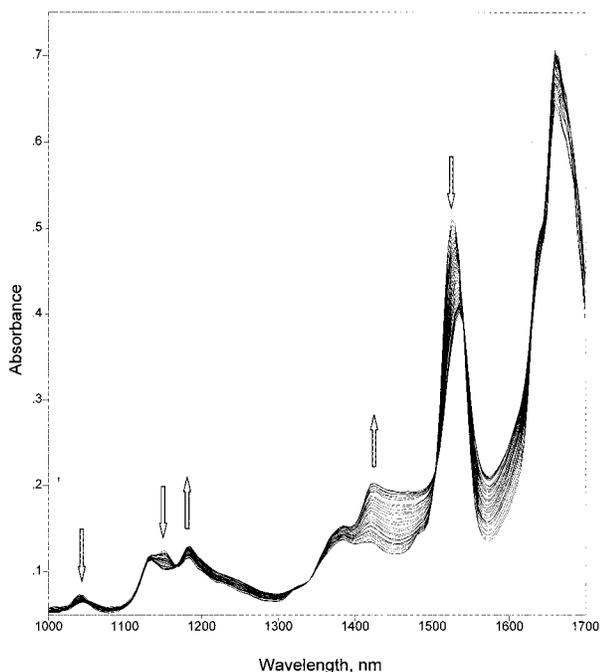


Figure 1. Near-infrared absorption spectral of the epoxy-amine mixture during an 8-h cure at room temperature (25 °C), shown at an interval of 15 min. Spectra were calculated from averaged absorbance of a square of  $30 \times 30$  pixels of images recorded with the NIR multispectral image instrument.

It was found that the intensity of the band at 1428 nm increases concomitantly with the reaction. This is as expected because this band has been assigned to the hydroxy group, and this group is formed from the epoxy group. Between 1100 and 1200 nm there are three bands. These bands can be attributed to different C–H groups, namely, the aromatic C–H at 1132 nm, the epoxy C–H at 1150 nm, and the aliphatic C–H at 1182 nm. The band at 1150 nm decreases significantly as the concentration of epoxy groups decreases in the mixture, whereas the 1182-nm peak increases because new aliphatic C–H bonds are created. The peak at 1132 nm remains constant because no aromatic C–H bonds are formed or broken during the reaction. The C–H combination of aromatics also is responsible for the large band at 1670 nm.

**Kinetics of Cure Reactions and the Effect of the Temperature.** *Kinetic Determination.* It is clear from the last paragraph that the kinetic of the epoxy-amine cure reaction can be monitored by use of one or all of three absorption bands: the epoxy band at 1150 nm, the hydroxy band at 1428 nm, and the amine band at 1543 nm. As described previously, the amine band at 1543 nm is due not only to the primary amine (at 1525 and 1543 nm) but also to the secondary amine as well (at 1543 nm). It is, therefore, not practical to use this band for kinetic determination because it would require the deconvolution of this band into two components. Kinetic determination can, therefore, be based on either the decrease of the epoxy band at 1150 and/or the increase of the hydroxy band at 1428 nm. On the basis of the reactions between epoxy and amine shown in Scheme 1, it is clear that the epoxy group is converted into an hydroxy group (through reaction with amine). The relative decrease in the absorbance of the epoxy group should, therefore, be the same as the increase in the absorbance of the hydroxy group. The relative decrease of the epoxy band at 1150 was plotted in Figure 2 together with the

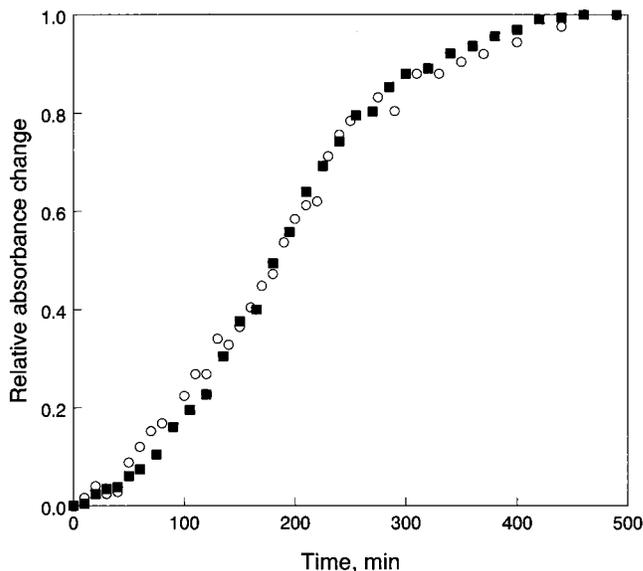


Figure 2. Relative absorbance changes of the epoxy band at 1155 nm (○) and of the hydroxy band at 1428 nm (■) of the epoxy-amine mixture at room temperature (25 °C). For clarity, both absorbance variations were plotted as positive.

relative increase of the hydroxy band at 1428 nm. As expected, the decrease of the epoxy band is the same as the increase of the hydroxy band. Both bands can, therefore, be used for kinetic measurements. However, it should be realized that error associated with the 1150-nm band is relatively larger than that of the 1428-nm band because the absorption coefficient of the epoxy band is lower than that of the hydroxy band. In fact, the absolute absorbance change of the 1150-nm band is only  $\sim 0.023$  whereas it is  $\sim 0.066$  for the 1428-nm band. Accordingly, the band at 1428 nm was used for the kinetic determination of cure reactions because it has larger changes, less errors, and no interference from other bands.

To increase the accuracy of the kinetic measurements using the 1428-nm band, images of the epoxy-amine mixture were recorded from 1350 to 1510 nm, not at every 5 nm but rather at 1-nm spectral intervals. The reaction was measured at four different temperatures: 25, 35, 45, and 55 °C. To correct for the effect of the temperature on the absorption coefficient, spectra were measured at the end of the reaction at room temperature. All measured absorbances were then corrected by the factor  $A_{T_0}/A_T$ , where  $A_{T_0}$  is the absorbance of the cured epoxy at room temperature and  $A_T$ , the absorbance of the cured epoxy at temperature  $T$ . The degree of cure reached at the end of the reaction were determined from the NIR spectrum of the cured epoxy measured with a NIR spectrophotometer equipped with a single-channel InGaAs detector. The measurements were performed at the epoxy band at 2201 nm at the beginning ( $t = 0$ ) and the end of the cure ( $t = 225$  min) at 55 °C. It is estimated, from the areas of this epoxy band, that 90% of all epoxy groups reacted during the cure. This value is comparable to other values reported in the literature. For example, it was reported that degrees of cure of a mixture of bisphenol A epichlorohydrin resin and 1,6-hexa-diamine at 30, 40, and 50 °C were 65, 78, and 82%, respectively.<sup>1</sup> A similar procedure was used to determine the degrees of cure for reactions at 25, 35, and 45 °C after 500, 350,

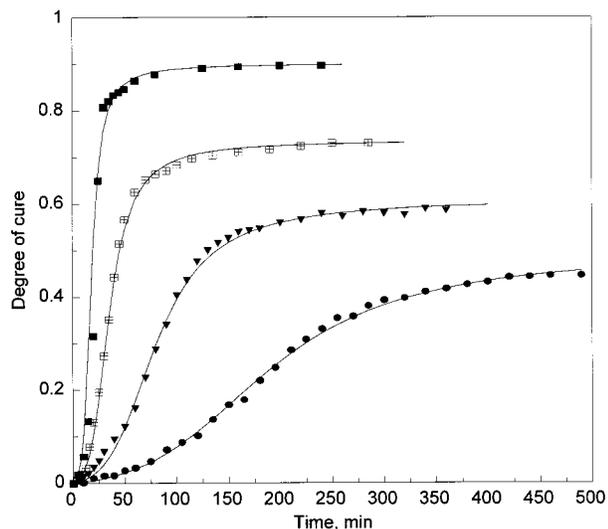


Figure 3. Degrees of cure as a function of time for the epoxy–amine mixture at different temperatures: 25 (●), 35 (▼), 45 (▣), and 55 °C (■). Solid curves are best fits of eq 1 to experimental data. Reaction rates  $k_a$  and  $k_b$  and degree of cure,  $\alpha$ , obtained from the fits for four temperatures are listed in Table 1.

Table 1. Rate Constants and Degrees of Cure of Poly(bisphenol A-co-epichlorohydrin) Glycidyl End Capped Epoxy by Eithylenetriamine at Different Temperatures

temp, °C	$k_a$	$k_b$	$\alpha_\infty$
25	0.00068	0.056	0.50
35	0.0010	0.109	0.61
45	0.0016	0.203	0.73
55	0.0019	0.330	0.90

and 275 min, and the results obtained are represented in Figure 3.

As illustrated in Scheme 1, in the initial step, epoxy reacts with amine to produce hydroxy–amine compound. This reaction proceeds uncatalyzed. The hydroxy group of the hydroxy–amine (and of the final products) catalyzes the subsequent reaction between amine and epoxy. This type of reaction is known as an autocatalyzed reaction. The hydroxy groups also can react with epoxy to form ether. Consequently, the overall reactions can be considered as uncatalyzed initiation, autocatalysis, and inhibition. Based on this model, the relationship between the degree of cure,  $\alpha$ , and rates of reactions can be expressed as<sup>24–26</sup>

$$d\alpha/dt = (k_a + k_b\alpha^n)(\alpha_\infty - \alpha)^m \quad (1)$$

In addition to the degree of cure  $\alpha$ , an additional term  $\alpha_\infty$  is used because the maximum cure in this case was 90% (at 55 °C). This empirical expression can be explained as follows: the reaction at the beginning is uncatalyzed and has a rate constant of  $k_a$ . Subsequently, the reaction proceeds via autocatalysis by hydroxy group with a rate constant of  $k_b$ . Because the O–H group is formed during the curing reaction, this term is multiplied by the

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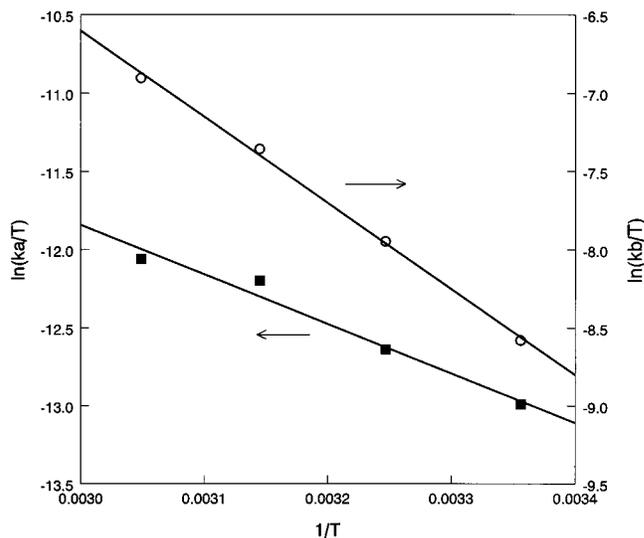


Figure 4. Arrhenius plot for  $k_a$  (■) and  $k_b$  (○).

Table 2. Activation Energies of Epoxy–Amine Reaction

	$E_a$ , kJ mol <sup>-1</sup>	ln A	$\Delta S^\ddagger$ , J K <sup>-1</sup> mol <sup>-1a</sup>	$\Delta H^\ddagger$ , kJ mol <sup>-1a</sup>	$\Delta G^\ddagger$ , kJ mol <sup>-1a</sup>
$k_a$	28.96	4.42	-216.9	26.36	91.00
$k_b$	48.36	16.66	-115.1	45.76	80.06

<sup>a</sup> Calculated at 25 °C.

degree of cure  $\alpha^n$  (i.e.,  $k_b\alpha^n$ ). Finally, the reaction becomes slower when  $\alpha$  approaches  $\alpha_\infty$  (inhibition).

The values of  $k_a$ ,  $k_b$ , and  $\alpha_\infty$ , at different temperatures were obtained by curve fitting of data obtained for the epoxy–amine mixture shown in Figure 3. The results are listed in Table 1. At all temperatures,  $k_b$  values are much larger than corresponding  $k_a$  values. For example,  $k_b$  is 82-fold larger than  $k_a$  at 25 °C. The difference becomes larger as the temperature increases; e.g., at 55 °C,  $k_b$  is 173 times higher than  $k_a$ . This is hardly surprising considering the fact that  $k_a$  is for uncatalyzed reactions whereas  $k_b$  is for reactions catalyzed by O–H groups. The values of  $m$  and  $n$  were found to be 0.91 and 1.63, respectively, which are comparable with values of 0.85 and 1.39 reported for similar a epoxy–amine system.<sup>1</sup>

**Effect of Temperature and Activation Energies of Cure Reactions.** Rate constants  $k_a$  and  $k_b$  are related to temperature by the Arrhenius equation:

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

where  $k$  is the reaction rate constant ( $k_a$  and  $k_b$ ),  $A$  is the Arrhenius preexponential factor,  $E_a$  is the energy of activation,  $R$  is the universal gas constant, and  $T$  is the absolute temperature. Plots of  $\ln k$  against  $1/T$  for  $k_a$  and  $k_b$  are shown in Figure 4. From these plots, corresponding  $A$  and  $E_a$  values were calculated and are listed in Table 2. The activation energy for the catalyzed reaction was found to be larger than that for the uncatalyzed reaction (48.36 and 28.96 kJ mol<sup>-1</sup>). Interestingly, the preexponential factor ( $\ln A$ ) for  $k_b$  is larger than that for  $k_a$ . Similar results were also obtained by other workers for epoxy–amine reactions.

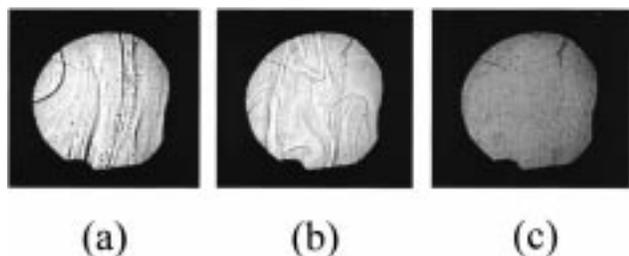


Figure 5. Images of epoxy-amine during a cure at 50 °C, recorded at 1428 nm and at different times:  $t = 0$  min (a),  $t = 7$  min (b), and  $t = 50$  min (c).

For example, in the reaction between bisphenol A epichlorohydrin resin and 1,6-hexanediamine, activation energies of and preexponential factors for  $k_a$  and  $k_b$  were found to be 40.75 and 65.43 kJ mol<sup>-1</sup>, and 9.51 and 22.0, respectively.<sup>1</sup>

The enthalpy, entropy, and free energy of the reactions can be calculated using the Eyring equation and  $E_a$  and  $A$  values.<sup>27</sup> Careful inspection of the values obtained (listed in Table 2) reveals that the uncatalyzed reactions ( $k_a$ ) are more favorable than the catalyzed reactions ( $k_b$ ) in term of enthalpy. However, the entropy for the catalyzed reactions is much more favorable than the uncatalyzed reactions so that when both enthalpy and entropy are taken into account, the entropy factor overcomes the enthalpy factor. As a consequence, the free energy ( $\Delta G^\ddagger$ ) for the catalyzed reactions is lower (80.06 kJ mol<sup>-1</sup>) than that for the uncatalyzed reactions (91.00 kJ mol<sup>-1</sup>). This indicates that the catalyzed reactions are much more favorable (i.e., lower  $\Delta G^\ddagger$  value). A variety of reasons may account for the large entropy effect observed in these reactions including the fact that the reaction mixture is very viscous. Because of the high viscosity, upon completing the initial uncatalyzed reaction, the amino-hydroxy product, the epoxy, and the amine cannot move away but rather are sequestered together. As a consequence, they are ready for the subsequent catalyzed reactions to occur.

**Inhomogeneity in the Epoxy-Amine Network.** The spatial inhomogeneity of a epoxy-amine cure was investigated with the NIR camera, which has relatively higher resolution (320 × 240 pixels with 10-bit resolution). All experiments in this section were carried out at 50 °C. Figure 5 show the NIR images of the epoxy-amine mixture at  $t = 0$ , 7, and 50 min. Spatial inhomogeneity was clearly observed at 0 and 7 min. This is probably due to a nonuniform mixing of the epoxy and amine. This inhomogeneity disappeared when the mixture reached and stayed steady at the preset temperature of 50 °C, which is ~10 min. The temperature fluctuation at the beginning is due to the experimental procedure. Specifically, in this experiment, the cell holder was preheated at 50 °C. When the cell reached that temperature, the heater was removed for ~2 min in order to insert the sample into the cell holder. It took ~10 min for the temperature of the sample to reach and to stay constant at 50 °C (the two components, epoxy and amine cannot be preheated at 50 °C because the reaction occurs very fast at this temperature so that two chemicals start to react during the mixing).

As described in the previous section, the kinetics can be determined by monitoring the hydroxy band at 1428 nm. Any

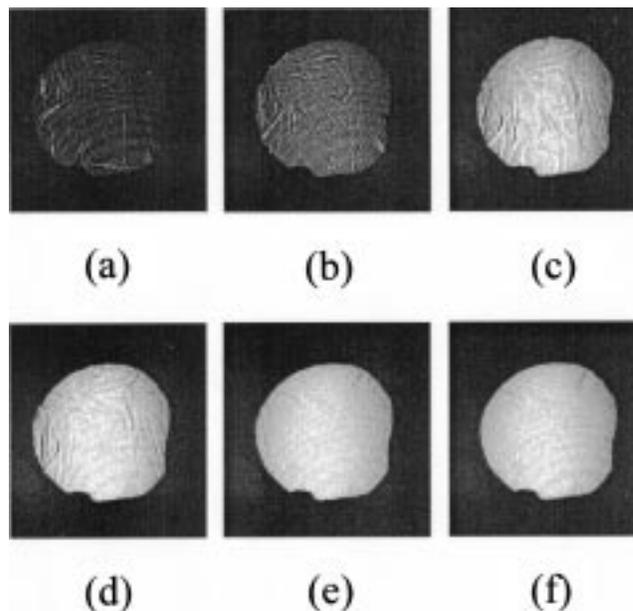


Figure 6. Differential images of the epoxy-amine, obtained by subtracting the image recorded at 1390 nm (background) from that at 1428 nm at different times: (a) 12, (b) 15, (c) 20, (d) 25, and (e) 30 min.

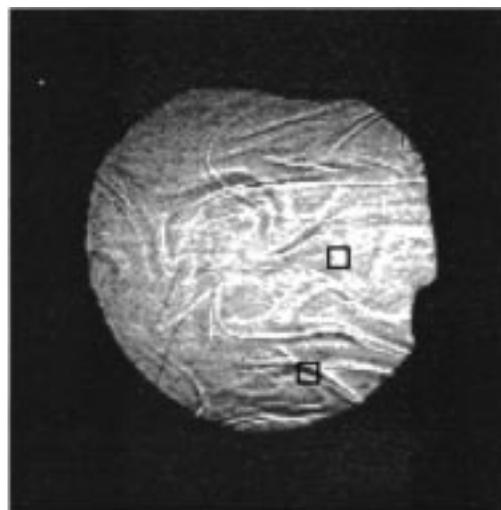


Figure 7. Enlarged image of epoxy-amine at 50 °C, recorded at 1428 nm and at 20 min after the reaction started. The two squares represent areas from which data from a single pixel were selected.

differences in the reaction rate within the epoxy-amine sample can be readily observed by subtracting the image recorded at 1390 nm (background signal, no band) from the image recorded at 1428 nm (hydroxy band). The resulting pictures are shown in Figure 6 for the epoxy-amine mixture at 50 °C recorded in the period between  $t = 12$  and 35 min. As described in previous section, most of the cure occurs in this time interval. It is evidently clear from the pictures that the cure reaction at any given time is not homogeneous, especially during the accelerated phase of the reaction (~15–20 min). When most of the cure is completed, the kinetic inhomogeneity becomes less pronounced.

Evidence for kinetic inhomogeneity can be clearly observed in the following example. Shown in Figure 7 is the image of the epoxy-amine at 50 °C, recorded at 1428 nm and at 15 min after the reaction started. It clearly illustrates the presence of inhomogeneity.

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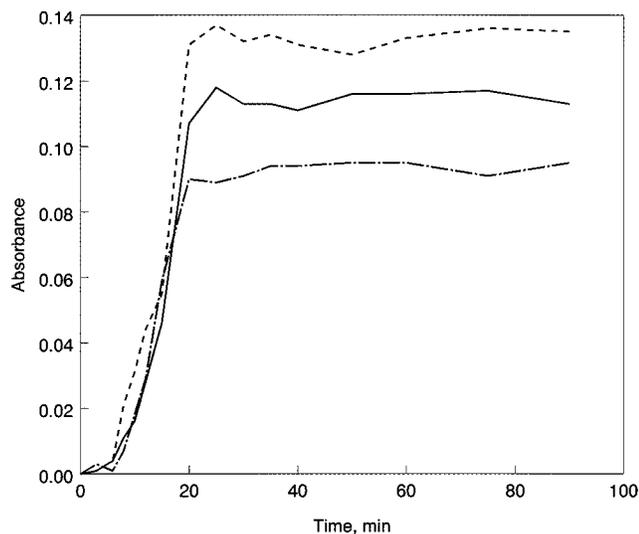


Figure 8. Changes in absorbance of the 1428-nm band, calculated from a single pixel corresponds to bright (---) and dark (-·-) spot in Figure 8. The solid curve was obtained by taking an average of  $60 \times 60$  pixel square of Figure 7.

geneity in the sample which is due mainly to the differences in reaction rates at different positions in the sample. The inhomogeneity can be better observed in Figure 8, which plots the changes in the absorbance at 1428 nm as a function of time for three different curves: the solid curve represents the averaged intensity of a  $60 \times 60$  pixel square; the dashed line represent the plot of a "bright" single pixel (as illustrated in Figure 7), and the point-line curve represents the plot of a "dark" single pixel (as illustrated in Figure 7). It is evident from the figure that the curing reaction is very much inhomogeneous, and because of this inhomogeneity, the degrees of cure reached at the end of the reaction will be different at different positions within the sample. The effect of the inhomogeneity can be quantitatively presented by fitting data collected at the three positions to eq 1 to obtain the degrees of cure  $\alpha_\infty$ . Best fits of experimental data, shown in Figure 9, indicate that up to 96% cure was obtained at the bright single pixel spot, 84% for the average of  $60 \times 60$  pixels, and only 70% for the dark single pixel spot. These results clearly demonstrated that, because of the kinetic inhomogeneity, up to 37% difference in the degrees of cure can be observed at different positions within the sample.

The inhomogeneity can only be observed when kinetics are simultaneously determined at different positions in the sample with a camera having high spatial resolution. In other words, the observed inhomogeneity is dependent on the spatial resolution of the imaging spectrometer. No inhomogeneity will be observed if signals from all pixels of the camera are averaged. This conclusion is based on the results in Table 3, which lists the degrees of cure for the dark and bright spots when different numbers of pixels were used for each spot to fit eq 1. When only one pixel was used per spot to fit, the degrees of cure were found to be 96 and 70% for the bright and dark spots, respectively. The  $\alpha_\infty$  value for the bright spot decreases to 84% whereas that for the dark spot increases to 73% when a square of  $3 \times 3$  pixels were used per spot for fitting. In fact, as the number of pixels per spot increases, the degree of cure for the bright spot decreases and that for the dark spot increases so that they approach the

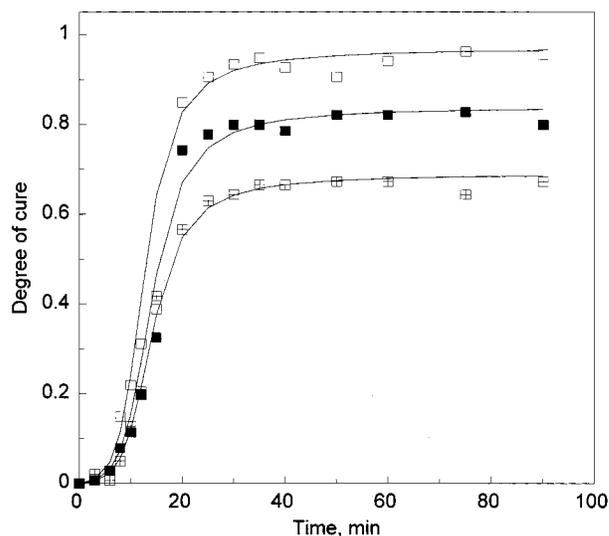


Figure 9. Degrees of cure as a function of time for the epoxy-amine mixture at three different positions in the sample: single pixel corresponds to the bright spot shown in Figure 8 ( $\square$ ), the dark spot ( $\blacksquare$ ), and to an average of  $60 \times 60$  pixels square ( $\blacksquare$ ).

Table 3. Degrees of Cure Calculated for the Bright and Dark Spots Shown in Figure 7 with Different Numbers of Pixels Per Spot

no. of pixels	degree of cure, %	
	bright spot	dark spot
1	96	70
$3 \times 3$	88	73
$5 \times 5$	88	77
$7 \times 7$	86	77
$9 \times 9$	86	79
$20 \times 20$	85	80
$30 \times 30$	84	82
$40 \times 40$	84	83
$50 \times 50$	84	84
$60 \times 60$	84	84

value of 84% which was obtained when a square of  $60 \times 60$  pixels were used for fitting. Of course, no inhomogeneity will be observed if a single-channel photodiode (such as those used in conventional NIR spectrometers) is used as detector.

In summary, it has been demonstrated that a sensitive multispectral imaging spectrometer capable of rapidly recording spectral images in the NIR region can be constructed with an acousto-optic tunable filter and an InGaAs focal plane array camera. The high sensitivity and fast scanning ability of the spectrometer make it suitable for kinetic determination of fast reactions. As expected, when used to determine the kinetics of the curing of epoxy by amine, the data obtained by this imaging instrument agree well with those obtained by FT-IR. The imaging spectrometer thus possesses all the advantages of conventional NIR spectrometers. It has, however, additional features which conventional IR spectrometers cannot offer, namely, its ability to provide kinetic information at different positions within a sample. The high spatial resolution and sensitivity of the InGaAs camera make it possible to determine the kinetic from data collected by a single pixel in the camera. The kinetics of curing of epoxy by amine, determined by this multispectral imaging instrument, shows that the reaction rates within the sample are very inho-

mogeneous, and because of this inhomogeneity, the differences in the degrees of cure reached at different positions within the sample can be as high as 37%. The cross-link density of the epoxy is, therefore, inhomogeneous. This will have a pronounced effect on a variety of materials including the advanced fiber reinforced composites (AFRC) as it is known that epoxy and amine hardener systems are widely used in the AFRC and that the mechanical properties of the AFRC are dependent on the cross-link density of the epoxy. However, despite its importance, because of lack of an imaging spectrometer, to date no information on the inhomogeneity of epoxy is available. The preliminary results on the inhomogeneity observed with this NIR imaging spectrometer are very encouraging and prompted us to concentrate our future efforts on increasing the spatial resolution of the instrument as it

is known that the inhomogeneity is dependent on its spatial resolution.

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