

# Evaluation of High Performance Fabric Under Light Irradiation

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**ABSTRACT:** To investigate the degradation characteristics of Kevlar fabric due to light irradiation, Kevlar fabric samples were irradiated using ATLAS 150S+ of xenon arc light for a range of time durations up to 168 h in this study. The UV-Vis spectrum showed that the transmittance and reflectance from the Kevlar samples decreased and the absorption increased along with the exposure time, showing a definite degradation tendency of Kevlar fabrics after light irradiation. The SEM pictures

showed that there are some residual deposits or corrosion on the surface of the fibers after irradiated for 168 h. The DSC curve, FTIR, and X-ray results showed the Kevlar fabric have a certain change but did not exhibit significant damage due to potential chemical interactions. © 2010 Wiley Periodicals, Inc. *J Appl Polym Sci* 120: 552–556, 2011

**Key words:** irradiation; DSC; FTIR; X-ray; fibers

## INTRODUCTION

Kevlar, a high performance fiber, has played an important role in various areas since it was invented by Kwolek and marketed by DuPont in 1971. It is a high strength, high modulus, and high heat-resistant organic material that is useful in a wide range of applications, including cables, ropes, conveyor belts, tire cords, sporting goods, fire-fighting clothing, body armor, and reinforcements in composites and laminates for inflatable missiles, satellites, and aerospace structures. As a result, it has received great attention from both industry and academia, and there have been some significant achievements in research on these fibers.<sup>1–8</sup> We have also reported results regarding the performance of such fibers under certain conditions.<sup>9–11</sup> Nowadays, the degradation property of the fibers under UV exposure has gained more attention,<sup>12–16</sup> including our previous research<sup>17</sup> on the UV-resistance of the fibers, where mechanical property of the Kevlar fiber after light irradiation was investigated. In this article, the degradation change of Kevlar fabric under light expo-

sure has been investigated to provide useful information for Kevlar fabric in the actual applications.

## EXPERIMENTAL

### Materials and condition

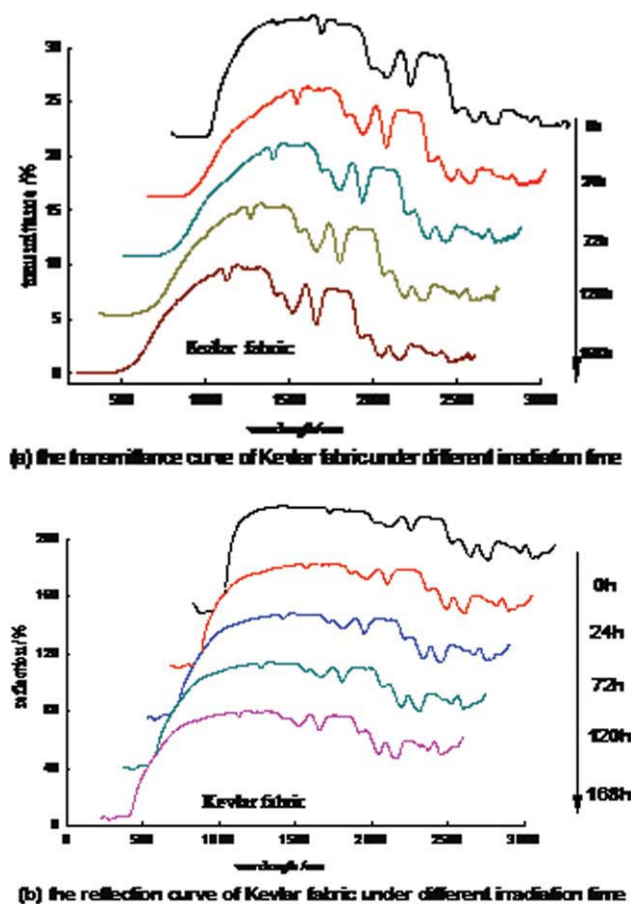
The Kevlar fabric samples (plain weave, weight per square meter is  $\sim 380 \text{ g m}^{-2}$ ) were irradiated using the ATLAS 150S+ of xenon arc light. The test was run at 60°C and 20% relative humidity in the light wavelength range of 300–800 nm in the chamber. Fabrics were continuously irradiated for 24, 72, 120, and 168 h, respectively.

After the irradiation, U4100 Spectrometer of Hitachi was used to characterize the optical properties of the Kevlar fabric, and the tested indices include the transmittance and reflectance. The scanning electron microscope (SEM) pictures of the fabric (the Kevlar fabric was made from Sichuan, China) after irradiation were also taken by using JSM-5600 LV. Then, the thermal analysis was conducted using differential scanning calorimeter (DSC822e; Mettler/Toledo, Greifensee, Switzerland). Samples of  $\sim 5 \text{ mg}$  was cut into tiny pieces and placed in a DSC pan and then heated from  $-50$  to  $550^\circ\text{C}$  at a scanning rate of  $10^\circ\text{C min}^{-1}$  under a constant flow of dry nitrogen.

Fourier transform infrared (FTIR) spectroscopy was also done using Nicolet 5700 FTIR spectrometer. The intensity profiles of the samples before and after light irradiation were measured by Ni filtered Cu-

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**Figure 1** The UV-Vis-IR spectrogram of Kevlar fabric under sunlight. [Color figure can be viewed in the online issue, which is available at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).]

K $\alpha$  irradiation ( $\lambda = 1.54\text{\AA}$ ) using a Rigaku D/Max-3AX WAXD diffractometer (Rigaku, Tokyo, Japan). The data were collected over the  $2\theta$ , range from 5 to 45°, at the scan rate  $8^\circ\text{min}^{-1}$ .

## RESULTS AND DISCUSSION

### Characterization of the optical properties of both original and irradiated fabric

The optical properties of Kevlar fabrics under simulated light irradiation were characterized, as shown in Figure 1, in the transmittance and the reflectance mode. From Figure 1, it can be seen that the transmittance and the reflectance of the fabrics decreased significantly with the irradiation time, especially during both the Vis and the UV ranges, so the absorbance as a whole increased with the time. It showed the time of exposure has a direct effect on Kevlar degradation.

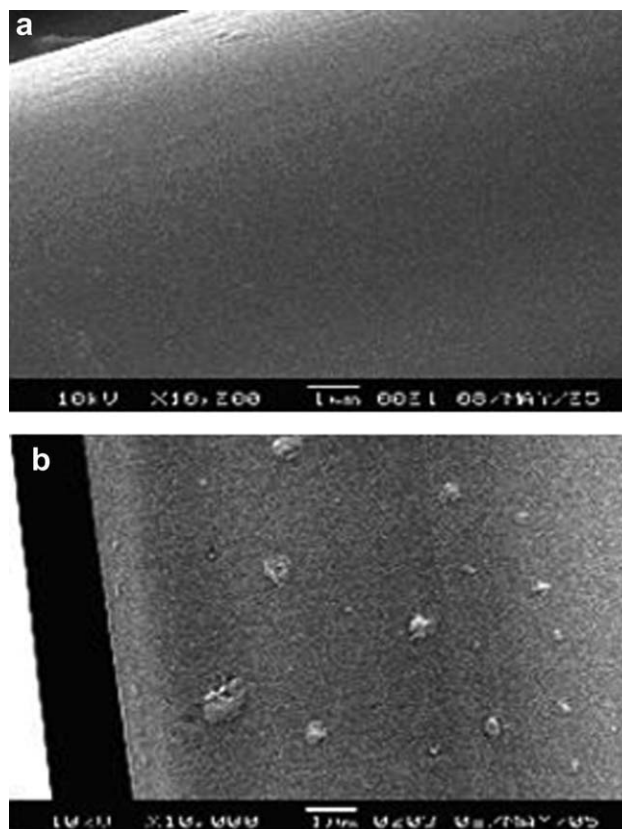
### SEM pictures of fabric under sunlight irradiation

The surface of Kevlar fabric after light irradiation was shown in Figure 2. The pictures showed that af-

ter 168 h irradiation, there are some deposits on the fiber surface, which implied certain decomposition of aramid polymers to light irradiation. It should be taken into account that the heat can play a role in degradation as well. In addition to 60°C temperature of the chamber, the light exposure generated additional heat on the samples. Such coupled attacking is very likely to accelerate surface decomposition of the samples and should be responsible for causing the surface irregularities observed in Figure 2(b).

### DSC curve of Kevlar fabrics

The DSC curves of the original and irradiated Kevlar fabric were shown in Figure 3. The DSC curves of the Kevlar fabrics showed similar shapes under different light exposure durations. The first endotherm (below 100°C) appeared to be related to the evaporation of surface water. In DSC scan of the original Kevlar sample [Fig. 3(a)], gradual exotherm began at  $\sim 400^\circ\text{C}$  and continued up to 540°C. It was likely that this exotherm corresponds to a crosslinking event within the Kevlar fibers of this fabric.<sup>18</sup> The exothermic peak temperature decreased a little with the light irradiation time as shown in Figure 3, i.e., approximately at 534°C for 168 h exposure.



**Figure 2** The SEM picture of Kevlar fabric: (a) the original fabric and (b) fabric irradiated for 168 h.

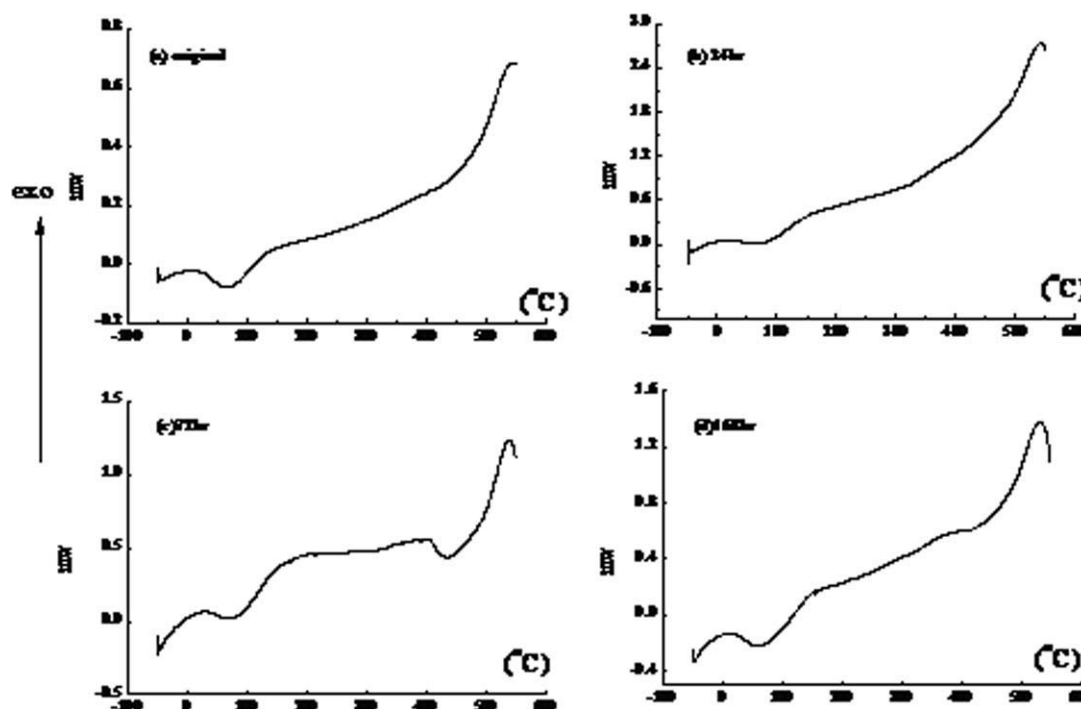


Figure 3 DSC curve of Kevlar fabric under light irradiation.

Crosslinking in polymers shows an exothermic fingerprint in DSC spectra due to the thermodynamically favorable conformation obtained by the formation of an interchain lattice structure. When order within the polymer structure is decreased as a result of thermal treatment, i.e., the case of polymer melting, then an endothermic event followed. Therefore, the destruction of interchain hydrogen bonds can be characterized as an endothermic event in the DSC spectra. No such endothermic event was detected in the Kevlar fabric DSC spectra. It is possible that an endothermic and exothermic event occurred simultaneously, where the dominant thermodynamic change being detected by the DSC.

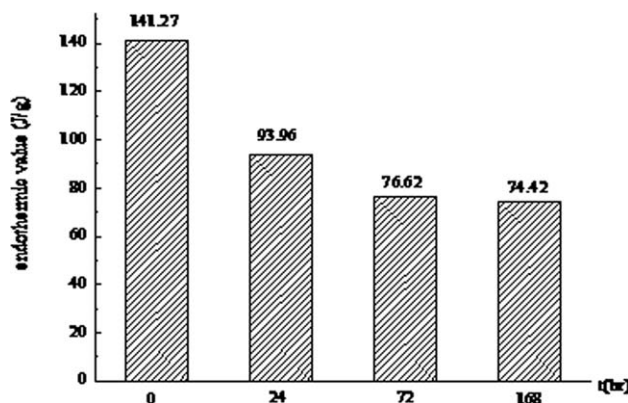


Figure 4 The endothermic value of Kevlar fabric at endothermic peak temperature ( $\sim 70^{\circ}\text{C}$ ).

Compared with the integral of the first endothermic peak area of the Kevlar fabric at about  $70^{\circ}\text{C}$ , the illustration was shown as Figure 4. It can be found with the longer irradiated time and the decreased endothermic energy per mass, which also implied that the Kevlar fabric have some inner structure change after light irradiation.

#### FTIR of the Kevlar sample

To study the inner change of these samples under light irradiation, the FTIR spectrum of samples were

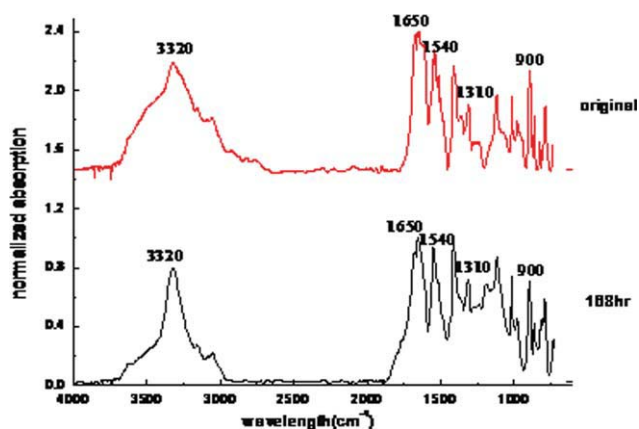


Figure 5 FTIR spectrum of Kevlar sample under different light time. [Color figure can be viewed in the online issue, which is available at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).]

collected. The spectra of the original and 168 h treated samples were illustrated in Figure 5.

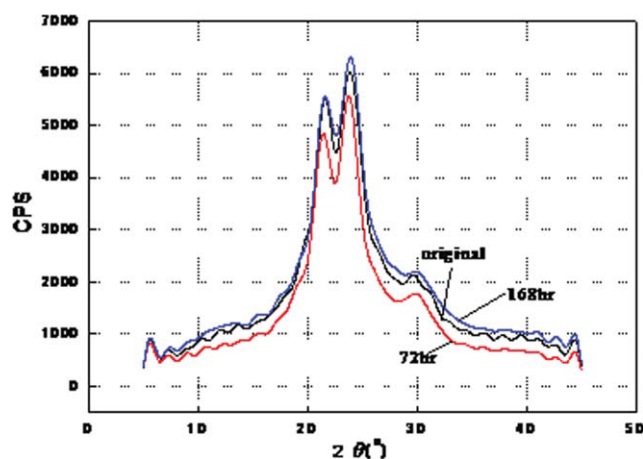
It can be found as follows:  $3320\text{ cm}^{-1}$  (amide A), N—H stretching vibration in an amide in *trans* form with a bonded hydrogen;  $1650\text{ cm}^{-1}$ , amide C=O stretching (amide I) for hydrogen bonded amide group;  $1540\text{ cm}^{-1}$ , coupled modes of N—H deformation and C—N stretching vibration (amide II);  $1310\text{ cm}^{-1}$ , combination of C—N stretching and N—H bending vibration (amide III).<sup>19,20</sup>

When compared between the two spectra, there was no obvious new peak appeared and no new chemical group formed on the surface of the samples as a result of degradation, but the intensity changed just a little.

The decrease in peak intensity and area was observed with increasing irradiation time at wave number  $\sim 3320\text{ cm}^{-1}$ , corresponding to the loss of hydrogen bonded amide functionality. This result indicated that the interchain hydrogen bond destruction is occurring within the Kevlar fabric that had been irradiated at 168 h.

After UV irradiation, the amide I absorbent peak's intensity increased a little, which may result from the interruption of the regular hydrogen bonding between CO and NH groups on adjacent chains owing to the chain scission and chain end group oxidation.

Besides, for the  $1310\text{ cm}^{-1}$  band (assigned to Ph—N band), the observed intensity increased, suggesting that the products with the nitrogen atom bonded to the aromatic ring react gradually. The  $900\text{ cm}^{-1}$  band, C—H out-of-plane bending of a single H on benzene ring decreased with the time, which indicated the substituent number started to increase on the aromatic rings.



**Figure 6** WAXD of fabric under light irradiation. [Color figure can be viewed in the online issue, which is available at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).]

**TABLE I**  
Crystallinity Changes of Kevlar Fabric

Sample	$2\theta$ (°)		FWHM (°)		$L_{hkl}$ (nm)		CI (%)
	(110)	(200)	(110)	(200)	(110)	(200)	
Original	21.59	23.83	2.63	2.63	3.045	3.058	75.82
Light, 72 h	21.43	23.74	2.61	2.61	3.069	3.081	72.43
Light, 168 h	21.58	23.90	2.95	2.95	2.715	2.726	71.76

### Wide-angle X-ray diffraction

At the same time, the X-ray diffraction of Kevlar samples under light for 72 and 168 h is illustrated as shown in Figure 6, along with that for the original sample.

Using the Scherrer equation,

$$L_{hkl} = \frac{k\lambda}{\omega \cos \theta} \quad (1)$$

where  $L_{hkl}$  (nm) is the weight average size of a crystallite perpendicular to its diffracting planes,  $k$  is a coefficient related with the crystallites' structures, and the definitions of  $L_{hkl}$  and  $\omega$  are always taken as 0.9 when  $\omega$  is the full-width at half-maximum (FWHM) and 1.0 when  $\omega$  is the integral breadth,  $\theta$  is the half of the Bragg angle  $2\theta$ ,  $\lambda$  is the wavelength of Cu-K $\alpha$  beam, and here  $\omega$  is the FWHM of the respective crystalline peaks. In this article,  $k = 0.89$  and  $\lambda = 1.5418\text{ \AA}$ .

The crystallinity and size of the lattice of the Kevlar samples are also summarized in Table I, where CI is the crystalline index and is defined as follows:

$$CI = 1 - \frac{A_a}{A} \quad (2)$$

$A_a$  is the diffraction area of the amorphous area obtained by peak fitting, and  $A$  is the total diffraction area of the corrected intensity profile. The data in the table showed that the crystallinity (CI) of the samples decreased with the light exposure time, and the reduction is steady but marginal. At 72-h exposure, the crystallite sizes in the direction (110) and (200) exhibited small change; however, after a prolonged irradiation after 168 h, such change grew significantly consistent with the DSC and FTIR results.

### CONCLUSIONS

In this article, the Kevlar fabric was exposed to light for different time, such as 24, 72, 120, and 168 h. The UV-Vis spectrum of Kevlar fabric showed the transmittance and the reflection of sample decreased, whereas the absorption increased with the time, which indicated the Kevlar fabric has degraded under light irradiation. The SEM pictures also



implied that the surface of Kevlar fabric has damaged under 168 h irradiation. The DSC, FTIR spectrum and X-ray results also showed Kevlar fabric have some change but not noticeable. In our future work, we will compare the samples with more specific differences such as in grade or diameter of the fiber, type of fabric weave, power of the irradiation source and distance from the sample (or irradiation dose), and surface temperature of the sample.

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## References

1. Li, X. G.; Huang, M. R. *J Appl Polym Sci* 1999, 77, 565.
2. Penn, L. *J Appl Polym Sci* 1979, 23, 59.
3. Cheng, M.; Chen, W. N.; Weerasooriya, T. *J Eng Mater Technol* 2005, 127, 197.
4. Su, F. H.; Zhang, Z. Z.; Guo, F.; Wang, K.; Liu, W. M. *Mater Sci Eng A* 2006, 4, 24.
5. Deteresa, S. J.; Allen, S. R.; Farris, R. J.; Porter, R. S. *J Mater Sci* 1984, 19, 57.
6. Yue, C. Y.; Sui, G. X.; Looi, H. C. *Compos Sci Technol* 2000, 60, 421.
7. Rao, Y. Q.; Farris, R. J. *Int J Fatigue* 2008, 30, 793.
8. Burgoyne, C. J.; Alwis, K. G. N. C. *J Mater Sci* 2008, 43, 7091.
9. Liu, X. Y.; Yu, W. D. *J Appl Polym Sci* 2006, 99, 937.
10. Liu, X. Y.; Yu, W. D. *J Appl Polym Sci* 2005, 97, 310.
11. Liu, X. Y.; Yu, W. D. *High Perform Polym* 2005, 17, 593.
12. Said, M. A.; Dingwall, B.; Gupta, A.; Seyam, A. M.; Mock, G.; Theyson, T. *Adv Space Res* 2006, 37, 2052.
13. Katangur, P.; Patra, P. K.; Warner, S. B. *Polym Degrad Stab* 2006, 91, 2437.
14. Katangur, P.; Warner, S. B.; Patra, P. K.; Kim, Y. K.; Mhetre, S. K.; Dhanote, A. *Mater Res Soc Symp Proc* 2004, 788, L8.
15. Zhang, H. P.; Zhang, J. C.; Chen, J. Y.; Hao, X. M.; Wang, S. Y.; Feng, X. X.; Guo, Y. H. *Polym Degrad Stab* 2006, 91, 27.
16. Lubin, G. *Handbook of Composites*; Van Nostrand Reinhold Company: New York, 1982.
17. Liu, X. Y.; Yu, W. D.; Xu, P. *Fibers Polym* 2008, 90, 455.
18. Downing, J. W.; Newell, J. A. *J Appl Polym Sci* 2004, 91, 417.
19. Mosquera, M. E. G.; Jamond, M.; Alonso, A. M.; Tascón, J. M. D. *Chem Mater* 1994, 6, 1918.
20. Park, S. J.; Seo, M. K.; Ma, T. J.; Lee, D. R. *J Colloid Interface Sci* 2002, 252, 249.