

Surface Modification and Physical Properties of Various UHMWPE-Fiber-Reinforced Modified Epoxy Composites

S. P. Lin,¹ J. L. Han,² J. T. Yeh,³ F. C. Chang,⁴ K. H. Hsieh^{1,5}

¹*Institute of Polymer Science and Engineering, National Taiwan University, Taipei, Taiwan 106*

²*Department of Chemical and Materials Engineering, National I-Lan University, I-Lan, Taiwan 260*

³*Department of Textile Science, Nanya Institute of Technology, Taoyuan, Taiwan 414*

⁴*Department of Applied Chemistry, National Chiao Tung University, Hsin-Chu, Taiwan 300*

⁵*Department of Chemical Engineering, National Taiwan University, Taipei, Taiwan 106*

Received 11 July 2006; accepted 3 November 2006

DOI 10.1002/app.25735

Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: Two surface modification methods—plasma surface treatment and chemical agent treatment—were used to investigate their effects on the surface properties of ultrahigh-molecular-weight polyethylene (UHMWPE) fibers. In the analyses, performed using electron spectroscopy for chemical analysis, changes in weight, and scanning electron microscope observations, demonstrated that the two fiber-surface-modified composites formed between UHMWPE fiber and epoxy matrix exhibited improved interfacial adhesion and slight improvements in tensile strengths, but notable decreases in elongation, relative to those properties of the composites reinforced with the untreated UHMWPE fibers. In addition, three kinds of epoxy resins—neat DGEBA, poly-

urethane-crosslinked DGEBA, and BHHBP-DGEBA—were used as resin matrices to examine the tensile and elongation properties of their UHMWPE fiber-reinforced composites. From stress/strain measurements and scanning electron microscope observations, the resin matrix improved the tensile strength apparently, but did not affect the elongation. © 2007 Wiley Periodicals, Inc. *J Appl Polym Sci* 104: 655–665, 2007

Key words: epoxy (DGEBA); polyurethane; ultrahigh-molecular-weight polyethylene (UHMWPE) fibers; tensile strength; interfacial adhesion in composites; plasma surface treatment; chemical agent treatment

INTRODUCTION

Epoxy resins are vitally important constituents in many manufacturing composite materials. Because of high glass transition temperature and being quite hard and brittle by nature, many thermoplastic polymers modified epoxy resin systems were developed to improve the toughness. The polyurethane (PU) modified epoxy resins^{1,2} exhibit a number of advantageous properties, including high processability, low shrinkage, good mechanical stability, and resistance to heat and chemical agents. Fiber-reinforced polymer composites are used widely because of their excellent properties, such as light weights and high specific strengths and moduli. Fibers that are excellent reinforcing materials include carbon fiber,^{3,4} glass fiber,^{5–8} aramid fiber, and ultrahigh-molecular-weight polyethylene (UHMWPE) fiber.^{9,10} The advantages of using UHMWPE fiber are its high tensile strength, high tensile modulus, light weight, and high resistance toward chemical and physical degradation. Unfortunately, it

also exhibits several drawbacks, such as a low surface energy and poor creep and heat resistances.

The interface between the reinforcing UHMWPE fiber and a matrix plays an important role in determining the mechanical properties of a UHMWPE fiber-reinforced composite. Many researchers have attempted to improve the surface properties of UHMWPE fibers through such processes as the T-peel strength of composites increased with the corona discharging treatment,¹¹ chemical grafting methods to make the UHMWPE wettable or capable of reaction with the matrix,¹² acid etching methods to roughen the surface and increase wettability,¹³ laser irradiation, oxygen-plasma treatment of the UHMWPE fiber increases the transverse tensile strength and failure strain of UHMWPE fiber/vinylester composites and changes the failure initiation site from the interface to interior of the UHMWPE fiber,¹⁴ and high-energy UV irradiation method may decrease the tensile properties but increases the crystallinity of the UHMWPE fiber.¹⁵

There are also many surface modification methods about aramid fiber reinforced polymer composites included plasma treatment,¹⁶ UV radiation method,¹⁷ and chemical agent treatment.^{18,19} Aramid fiber is a polar fiber that adheres well to the polymer matrix in the composite because of attractive hydrogen bonding and other polar interactions.

Correspondence to: K. H. Hsieh (khhsieh@ntu.edu.tw).

Contract grant sponsor: National Science Council, Taiwan; contract grant number: NSC 92-2622-E-011-020.

Journal of Applied Polymer Science, Vol. 104, 655–665 (2007)
© 2007 Wiley Periodicals, Inc.



In this study, two UHMWPE fiber surface modification methods included plasma and chemical agent surface treatments were applied to investigate the resulting surface properties using electron spectroscopy for chemical analysis (ESCA), weight change methods, and scanning electron microscope (SEM) observations. In addition, we used three kinds of epoxy resin matrices—neat DGEBA, PU-crosslinked DGEBA, and BHHBP-grafted DGEBA—to examine the tensile and elongation properties of various reinforced composites. SEM observations of fracture surfaces suggested the existence of improved interfacial adhesion and wet-out properties.

EXPERIMENTAL

Materials

The materials used in the research are listed in Table I. Epoxy resin (DGEBA; diglycidyl ether of bisphenol A; EEW = 186) and PBA 1000 polyol (Poly(tetramethylene adipate) glycol, M.W. = 1000) were heated and degassed under vacuum overnight prior to use.

Preparation of PU-crosslinked DGEBA resin

Figure 1 displays FTIR spectra recorded during the synthesis of the PU-crosslinked DGEBA. A broad peak for the OH groups (3500 cm^{-1}) of PBA 1000 polyol

appears in Figure 1(a) in the spectrum of the initial state of the reaction. Purging with dried nitrogen gas was performed to remove both air and moisture from the reaction kettle before 2 equiv. of MDI and 1 equiv. of PBA 1000 polyol were added [Fig. 1(b)]. In the middle stages of the reaction, the peak intensity of the signal of the OH groups (3500 cm^{-1}) decreased gradually and eventually disappeared while that of the NCO groups (2270 cm^{-1}) reduced to half of its original intensity (based on the peak of the 1,4-disubstituted benzene units at 840 cm^{-1}); in addition, a signal for the carbonyl groups (C=O) of urethane linkages (1740 cm^{-1}) was generated. At this point, DGEBA was added into the reaction system, whose spectrum appears in Figure 1(c). In the final stage of the reaction, the peak intensity of the residual NCO groups (2270 cm^{-1}) reduced continuously until it finally disappeared [Fig. 1(d)]. The changes in the peak intensities of the carbonyl (1740 cm^{-1}) and NCO (2270 cm^{-1}) groups indicates the progress of the chemical reaction toward the PU-crosslinked DGEBA. The molecular structure of the PU-crosslinked DGEBA is illustrated below.

Preparation of BHHBP-grafted DGEBA resin

4,4'-Bis(6-hydroxyhexyloxy)biphenyl (BHHBP) was synthesized from 4,4'-biphenol and 6-chloro-1-hexa-

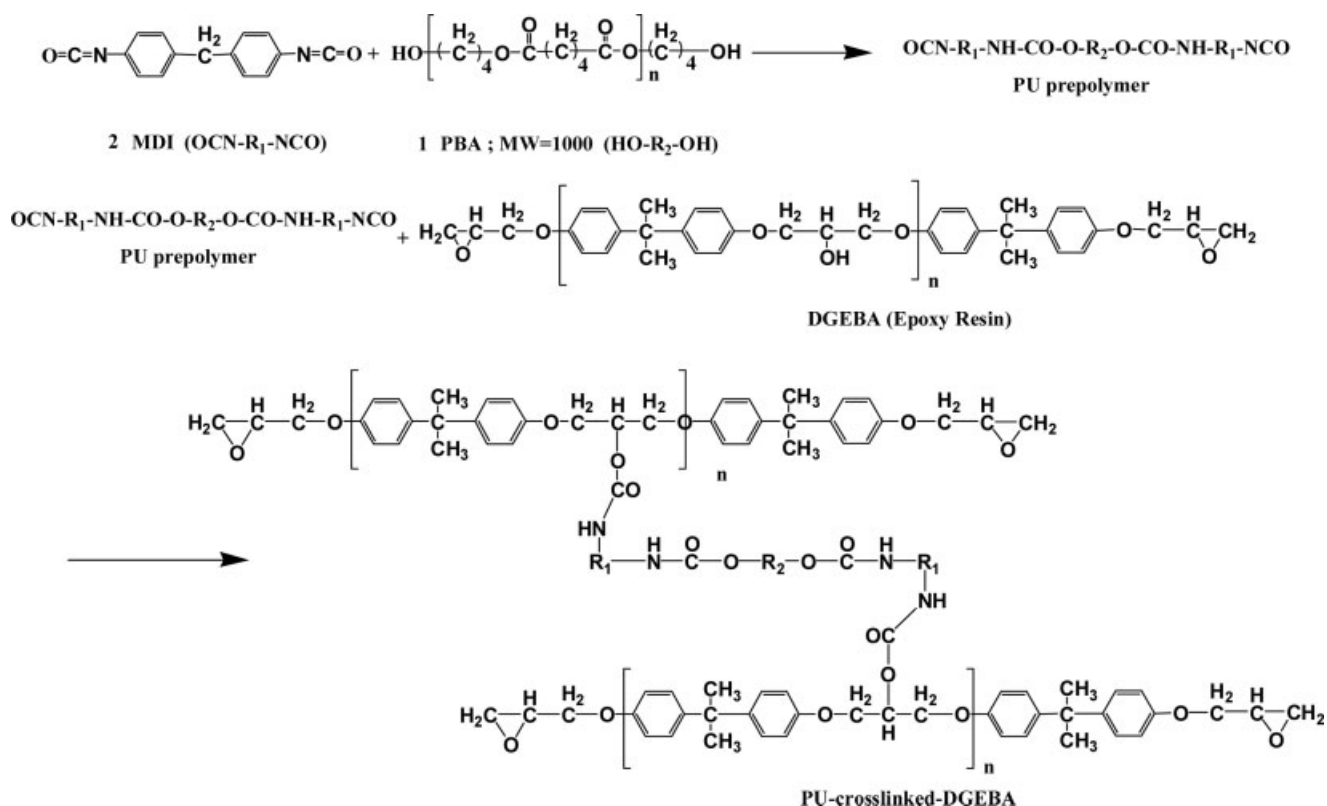
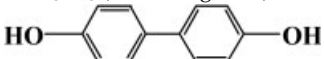


TABLE I
Materials

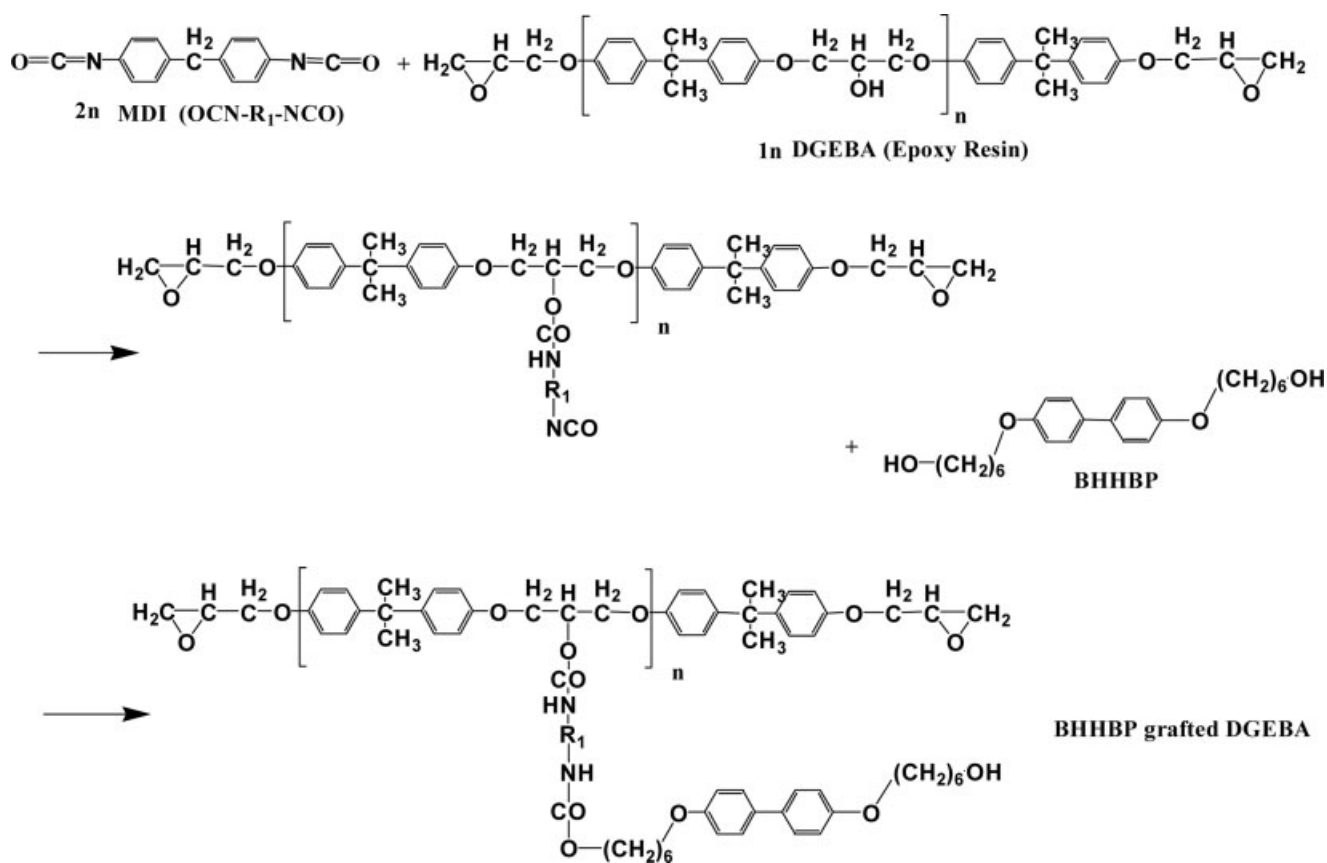
Designation	Description
UHMWPE fiber	Spectra @ 900 Denier 1200
Kevlar fiber	Technora @ T-200
Epoxy resin	DGEBA; diglycidyl ether of bisphenol A, EEW = 186 (Dow Chem.)
PBA 1000 (polyol)	Poly(tetramethylene adipate) glycol, M.W. = 1000 (Tai Gin, Taiwan)
MDI	4,4'-Diphenyl methane diisocyanate (TCI Chem.)
TDMP	2,4,6-Tri(dimethylaminomethyl) phenol (Jin-Men Chem., Taiwan)
DBSA	Dodecylbenzene Sulfonic Acid, $-\text{CH}_3(\text{CH}_2)_{11}\text{C}_6\text{H}_4\text{SO}_3\text{H}$ (Acros Organics)
Decalin	Decahydronaphthalene, $\text{C}_{10}\text{H}_{18}$ (Acros Organics)
4,4'-Biphenol	 (Acros Organics)
6-chloro-1-hexanol	$\text{Cl}-(\text{CH}_2)_6-\text{OH}$ (Acros Organics)
Acetone	2-propanone (Acros Organics)

mol as described previously.²⁰ Figure 2 displays FTIR spectra recorded during the synthesis of the BHHBP-grafted DGEBA. DGEBA was placed into a reaction kettle into which dry nitrogen gas was introduced to

remove both air and moisture. A suitable amount of 4,4'-diphenylmethane diisocyanate (MDI) was then added into the kettle and mixed with DGEBA [Fig. 2(a)]. The changes in the intensity of the peak for the isocyanate group (NCO , 2270 cm^{-1}) were monitored periodically. When the peak intensity of the isocyanate group reached half of its original value (based on the peak of the 1,4-disubstituted benzene units, 840 cm^{-1}), the OH groups on the side chains of the epoxy resin had reacted completely with the MDI [Fig. 2(b)]. BHHBP was added into the kettle. When the peak for the isocyanate groups disappeared, the OH groups of the BHHBP had reacted completely with the NCO groups of the MDI [Fig. 2(c)]. The molecular structure of BHHBP-grafted DGEBA is illustrated below.

Curing of PU-crosslinked DGEBA resin and BHHBP-grafted DGEBA resin

Various ratios of modified DGEBA resins and 3 phr curing agent (TDMP) were mixed with vigorous stirring and then placed under vacuum for several minutes to eliminate all of the bubbles produced during the course of the agitation. The individual mixtures were poured into a Teflon-coated aluminum mold and



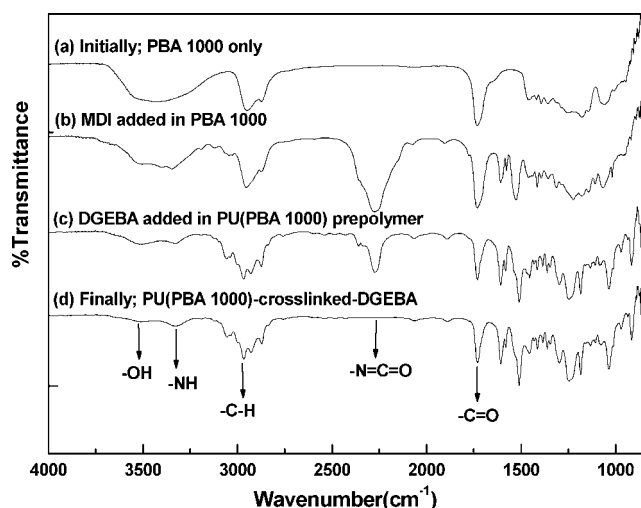


Figure 1 FTIR spectra of intermediates obtained during the synthesis of the PU(PBA 1000)-crosslinked DGEBA: (a) initial state; PBA 1000 only; (b) MDI added to PBA 1000; (c) DGEBA added to PU(PBA 1000) prepolymer; (d) final state; PU (PBA 1000)-crosslinked DGEBA.

pressed at 100 kg/cm^2 and 75°C for 1 h and then they were postcured at 150 kg/cm^2 and 90°C for 2 h.

Surface modification of UHMWPE fibers through treatment with plasma and chemical agents

For surface cleaning, the UHMWPE fiber was treated as follows:²¹

1. Immersion in a nonpolar solvent (benzene) for 1 h at room temperature;
2. immersion in a polar solvent (ethanol) for 1 h at room temperature;
3. immersion in distilled water for 1 h at room temperature; and
4. dried in an oven overnight at 60°C .

The discharge power of the plasma treatment apparatus was adjustable over the range from 0 to 200 W. In these experiments, four plasma treatment times (1, 5, 10, and 20 min) were selected using constant power (200 W). After plasma treatment, the fiber was exposed to the ambient atmosphere so that it would react with oxygen in the air.

For chemical agent treatment, the fiber was subjected to plasma treatment for 10 min and then immersed immediately into a dodecylbenzene sulfonic acid (DBSA)/decahydronaphthalene (decalin) mixture. The existence of DBSA was taken as an acid etching agent in the DBSA/decalin mixture for the acid etching process. The chemical treatment process was performed using four different DBSA weight ratios (0, 10, 20, and 30 wt %) and temperatures (25, 70, 80, and 90°C) to examine the effects of the DBSA concentration and the temperature. After treatment

with the chemical agent, the UHMWPE fibers were washed three times with ethanol and dried in oven overnight at 60°C .

Preparation of UHMWPE fiber- and aramid fiber-reinforced composites

The PU-crosslinked DGEBA (or BHHBP-grafted DGEBA) and 3 phr curing agent (TDMP) were mixed with vigorous stirring and then placed in a resin tank. Acetone was used to dilute the PU-crosslinked DGEBA and BHHBP-grafted DGEBA, respectively, to facilitate the impregnation of the UHMWPE and aramid fibers in the drum-type winding machine. After the prepregs had been wound up, they were heated in an oven at 60°C for 30 min to remove any residual acetone. Unidirectional (packing angle: 0°) aramid fiber/DGEBA, UHMWPE fiber/PU-crosslinked DGEBA, and UHMWPE fiber/BHHBP-grafted DGEBA composites containing the two different surface-treated UHMWPE fibers were fabricated using eight plies of manufactured prepregs; the dimensions of the compression mold were $200 \times 200 \times 1 \text{ mm}$ (length \times width \times thickness). The prepregs were stacked and compression molded at 100 kg/cm^2 and 75°C for 1 h and then postcured at 150 kg/cm^2 and 90°C for 2 h. For mechanical testing, the various composite specimens were cut into smaller sizes using a hydraulic power cutting machine. The fiber contents of the cured composites of the UHMWPE fiber reinforcement materials were obtained by etching of the resin in 80% HNO_3 solution under reflux for 4 h and then recording the weight loss.²²

Test methods

Infrared spectra were recorded using a BIO-RAD FTS-40 FTIR spectrophotometer operated at a resolution of

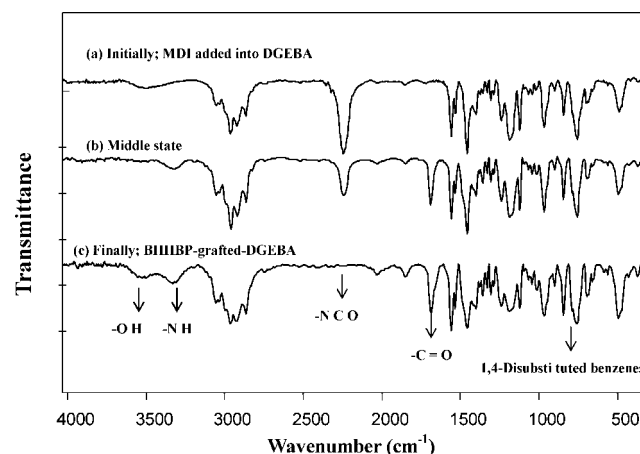


Figure 2 FTIR spectra of intermediates obtained during the synthesis of the BHHBP-grafted DGEBA: (a) initial state; MDI added into DGEBA; (b) middle state; (c) final state; BHHBP-grafted DGEBA.

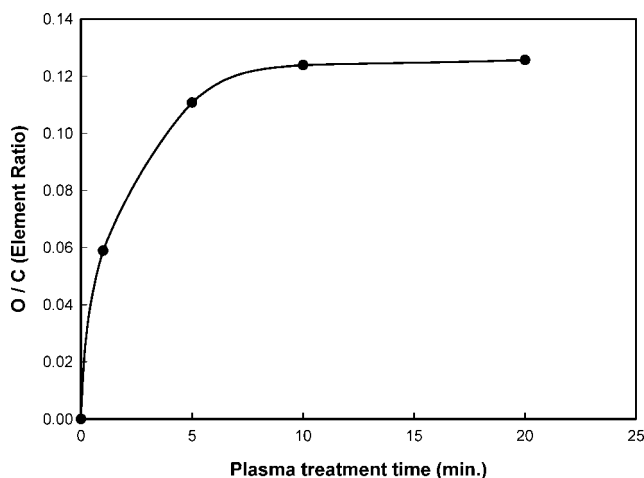


Figure 3 Element surface chemical analysis (ESCA) of UHMWPE fibers after plasma treatment.

4 cm^{-1} . ESCA was performed using a VG Scientific MT-500 chemical analyzer. Morphological studies were performed using a Tescan 5136 MM SEM. The stress/strain properties of the various UHMWPE fiber-reinforced composites were measured according to ASTM-D3039.

RESULTS AND DISCUSSION

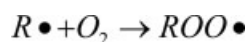
Plasma treatment of UHMWPE fibers

Figure 3 displays the ESCA result of the fiber surface modified through plasma treatment. The degree of oxidation increased rapidly upon increasing the plasma treatment time, but remained constant after 10 min. During plasma treatment, UHMWPE strands underwent both scission and dehydrogenation, causing micropits to be introduced into the fiber surface through etching. It is believed that such an oxidation process through plasma treatment would improve the degree of interfacial adhesion between the fiber and the resin matrix. The schematic illustrations for the formation of oxygen-containing groups are shown below:²³

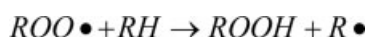
Initiation:



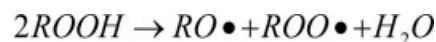
Forming a peroxy radical:



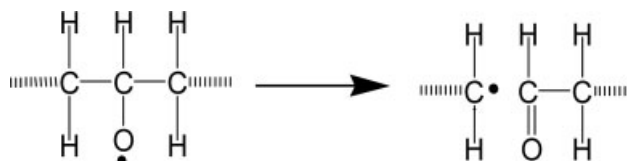
Or a hydroperoxide and new radical:



Chain scission:



Or disproportionation:



Crosslinking:



Figure 4 displays SEM images of the UHMWPE fiber surface modified through plasma treatment; the results are consistent with those of the ESCA analysis. The original UHMWPE fiber surface was smooth [Fig. 4(a)]. Plasma treatment induced micropits to appear on the UHMWPE fibers' surfaces, especially in the amorphous areas of the fiber surface [Fig. 4(b,c)]. The longer the plasma treatment time, the greater the extent of oxidation of the UHMWPE fiber surface and the greater the number of micropits. The presence of these oxygen-containing functional groups improved the interfacial properties between the UHMWPE fiber and the DGEBA matrix, but caused the strength of the UHMWPE fiber to decrease because of the corrosion of the surface structure. Thus, the optimal plasma treatment time for the UHMWPE fiber to provide the strongest reinforced fiber material was 10 min.

Chemical treatment of UHMWPE fibers

Figure 5 displays the weight changes of the UHMWPE fibers after treatment with a chemical agent. The weight change increased clearly upon increasing the acid (DBSA) weight ratio in the chemical agent (DBSA/decalin) mixture. This result confirms that DBSA reacted with the activated surfaces of the UHMWPE fibers formed after plasma treatment mentioned before. At a constant DBSA content in the chemical agent, however, different treatment temperatures had no apparent effect on the weight change; i.e., the temperature during chemical treatment is not a factor affecting the progress of the reaction. We confirmed the accuracy of this analytic method by using pure decalin solvent as the chemical agent; the weight changes of the pure-decalin-treated UHMWPE fibers

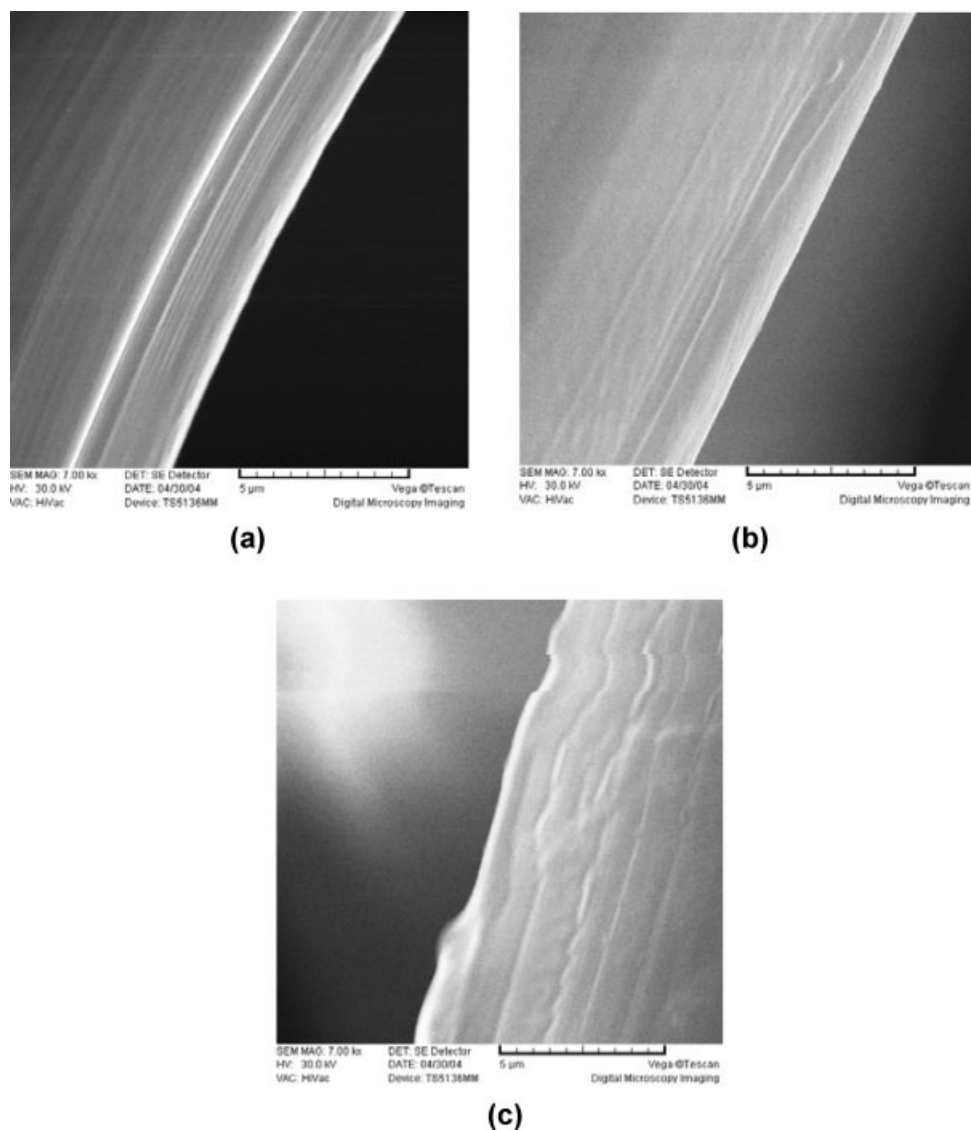


Figure 4 SEM images of UHMWPE fibers obtained after plasma treatment for various times: (a) untreated fiber, and fiber subjected to plasma treatment for (b) 5 and (c) 20 min.

were almost invariable at the four treatment temperatures.

Figure 6 presents SEM images of the UHMWPE fiber surfaces after modification through chemical agent treatment at 70°C using four different DBSA weight ratios. As indicated in Figures 6(b–d), a greater DBSA weight ratio in the chemical agent led to an increase in the number of rough and corrugated protuberances on the surface of UHMWPE fiber; the as-received fiber surface was smooth [Fig. 6(a)]. Thus, the SEM observations are consistent with the results of the weight-change analyses in Figure 5. For the manufacture of the following UHMWPE fiber-reinforced composite material, the UHMWPE fibers that had been subjected to chemical treatment with the chemical agent containing 30 wt % DBSA at 25°C.

Mechanical properties of UHMWPE fibers reinforced PU-crosslinked DGEBA composites

Table II lists the mechanical properties of different composites formed from the neat DGEBA matrix mixed with the variously modified UHMWPE fiber surfaces. The fiber contents of the three kinds of composites were maintained almost constant in range from 34.2 to 34.6 vol % such that the mechanical properties of the three composite systems would be compared fairly. Table II indicates that the two UHMWPE fiber surface modification methods (plasma and chemical agent treatment) led to surface-treated UHMWPE fiber-reinforced composites exhibiting slightly improved tensile strengths relative to that of the original UHMWPE fiber-reinforced composite. The tensile strengths of the systems were affected by two compet-

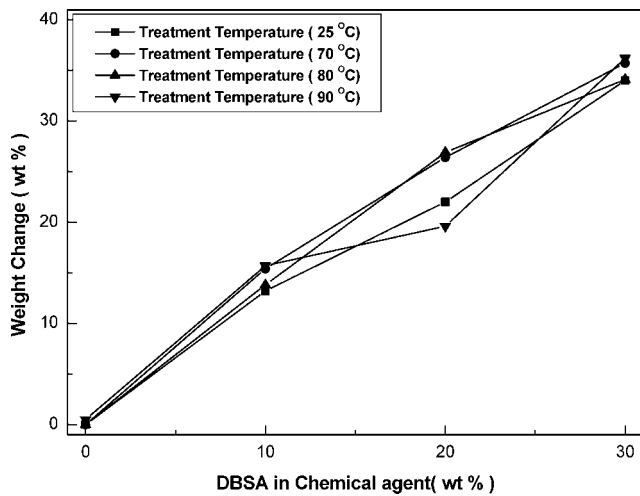


Figure 5 Effects of the temperature and amount of chemical agent on the weight changes of the chemically treated UHMWPE fibers.

ing effects: (a) degradation of the UHMWPE fiber strength caused by scission and dehydrogenation reactions of its surface and (b) improved interfacial adhesion between the UHMWPE fibers and the neat

DGEBA matrix. As a result, the tensile strengths of the composites containing the surface-treated fibers increased only slightly relative to that of the original UHMWPE fiber-reinforced composite.

The elongation properties of the composites formed using both types of surface-treated UHMWPE fibers decreased relative to that of the original UHMWPE fiber reinforced composite. Because the UHMWPE fibers are nonpolar materials and the neat DGEBA matrix was polar, the interfacial adhesion within the original UHMWPE fiber-reinforced composite was quite poor. The SEM image shown in Figure 7(a) reveals that the original composite underwent a pull-out fracture mechanism during tensile testing. After plasma surface modification of the UHMWPE fibers, interfacial adhesion within the fiber-reinforced composites increased because of the presence of polar functional groups on the modified UHMWPE fibers' surfaces. So, it would obviously decrease the elongation of the plasma treated UHMWPE fiber/DGEBA composites, as indicated in the SEM image in Figure 7(b).

Figure 8(a–c) indicates that the composites containing both kinds of UHMWPE-surface-treated fibers exhibited better wetting properties than did the origi-

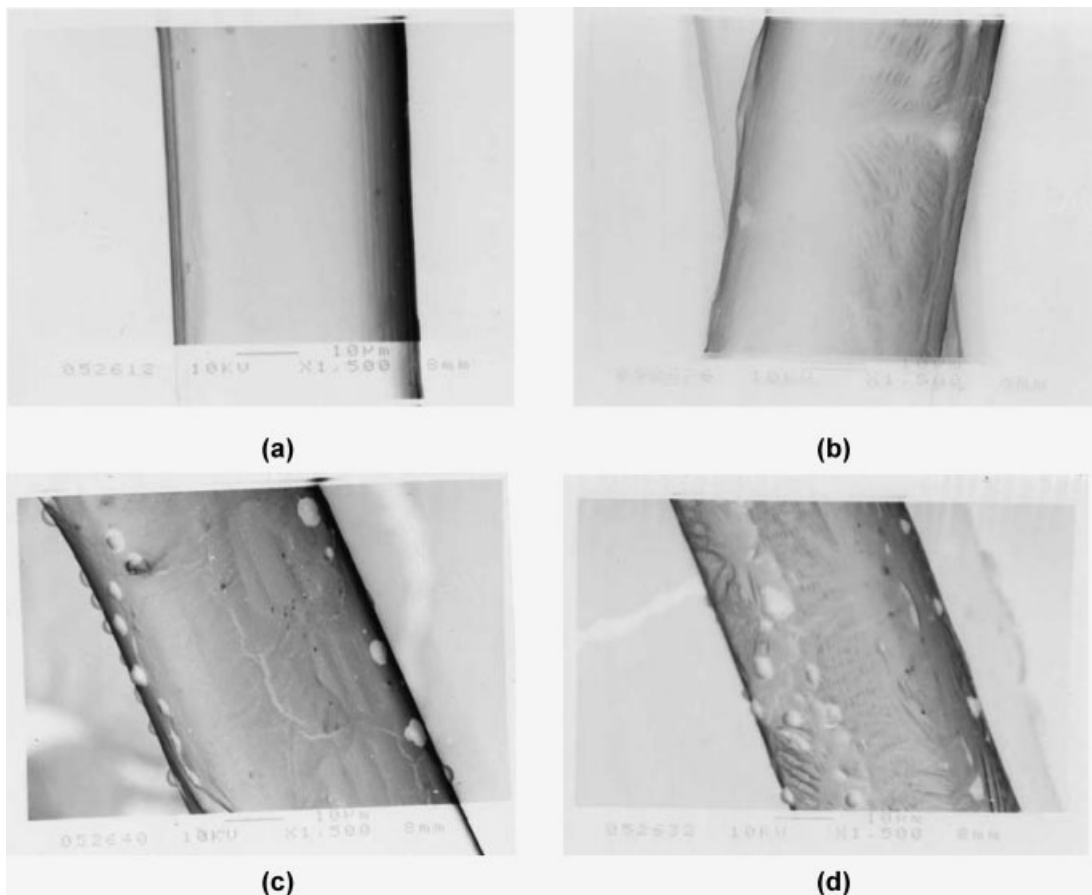


Figure 6 SEM images of UHMWPE fibers exposed to various proportions of the chemical agent at 70 °C: (a) 0 wt %, (b) 10 wt %, (c) 20 wt %, and (d) 30 wt % DBSA in chemical agent.

TABLE II
Mechanical Properties of Composites Formed from Surface Modified Fibers

Composite system	Fiber content (vol %)	Tensile strength (σ ; MPa)	Elongation (%)
Original UHMWPE fiber/ neat epoxy resin composite	34.6	526.7 \pm 4.4	14.0 \pm 1.2
Plasma treated UHMWPE fiber/ neat epoxy resin composite	34.2	543.4 \pm 5.4	7.8 \pm 0.4
Chemical agent treated UHMWPE fiber/ neat epoxy resin composite	34.5	537.3 \pm 5.2	8.1 \pm 0.5

nal fiber-reinforced composite. In the following experiments, the effects that various modified DGEBA matrices have upon the mechanical properties of composites were studied using composites manufactured from untreated and plasma-treated UHMWPE fibers.

Table III lists the mechanical properties of the UHMWPE fiber-reinforced composites prepared from the various modified DGEBA matrices. The fiber contents of the three kinds of composites were maintained within the range from 36.0 to 38.0 vol %. Each tensile modulus was measured by determining the slope of the stress/strain curve from 0.1 to 0.5% strain. The tensile strengths of the plasma-treated UHMWPE fiber reinforced composites were higher than those of the untreated UHMWPE fiber-reinforced composites. This phenomenon was caused by the two competitive effects—degradation of the fibers themselves and improved interfacial adhesion between the UHMWPE fibers and the epoxy matrix. From a comparison of the composite systems formed from neat DGEBA and from the two modified DGEBA matrices, we found that the choice of resin matrix played an important

role in determining the tensile strength. The results listed in Table III and presented in Figure 9(a) indicate that the PU-crosslinked DGEBA matrix composites exhibited higher values of tensile strengths (\sim 30% greater for the untreated UHMWPE fiber-reinforced system and 27% greater for the plasma-treated UHMWPE fiber-reinforced system) than did the neat DGEBA matrix composites. This behavior was due to two effects: (a) crosslinking of the PU prepolymer with the pendent hydroxyl groups of DGEBA and (b) the softness of the PU prepolymer.²⁴ The BHHBP-DGEBA matrix composites also exhibited the same trend: the tensile strengths were \sim 32% higher for the untreated UHMWPE fiber-reinforced system and 30% higher for the plasma-treated UHMWPE fiber-reinforced system than they were for the neat DGEBA matrix composites. These phenomena were due to (a) the reactions of the rigid-rod-like BHHBP with the pendent hydroxyl groups of DGEBA and (b) the BHHBP-modified DGEBA forming short-fiber-reinforced polymer composites. The untreated-UHMWPE-fiber-reinforced DGEBA composite exhibited a tensile strength

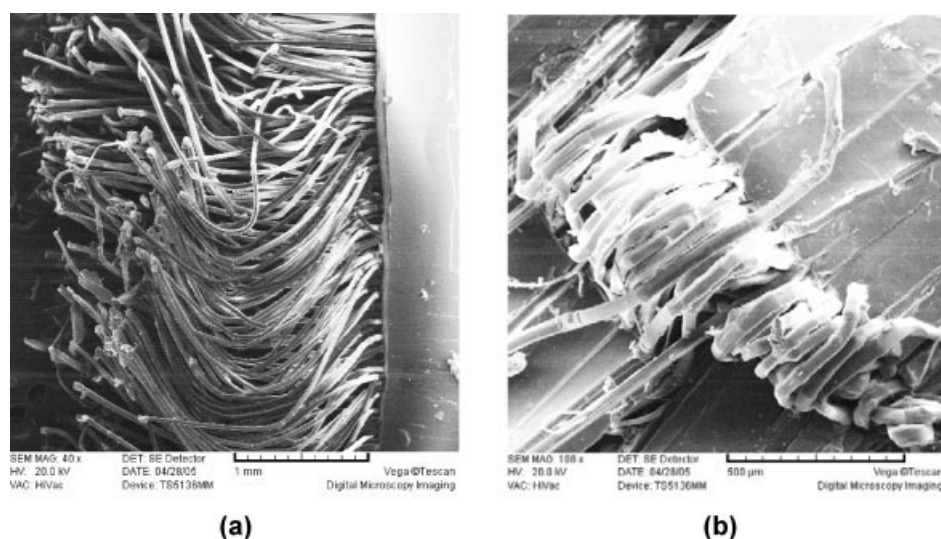


Figure 7 SEM images of various fracture surfaces of composites: (a) Original and (b) Plasma-treated UHMWPE fiber/ DGEBA composite.

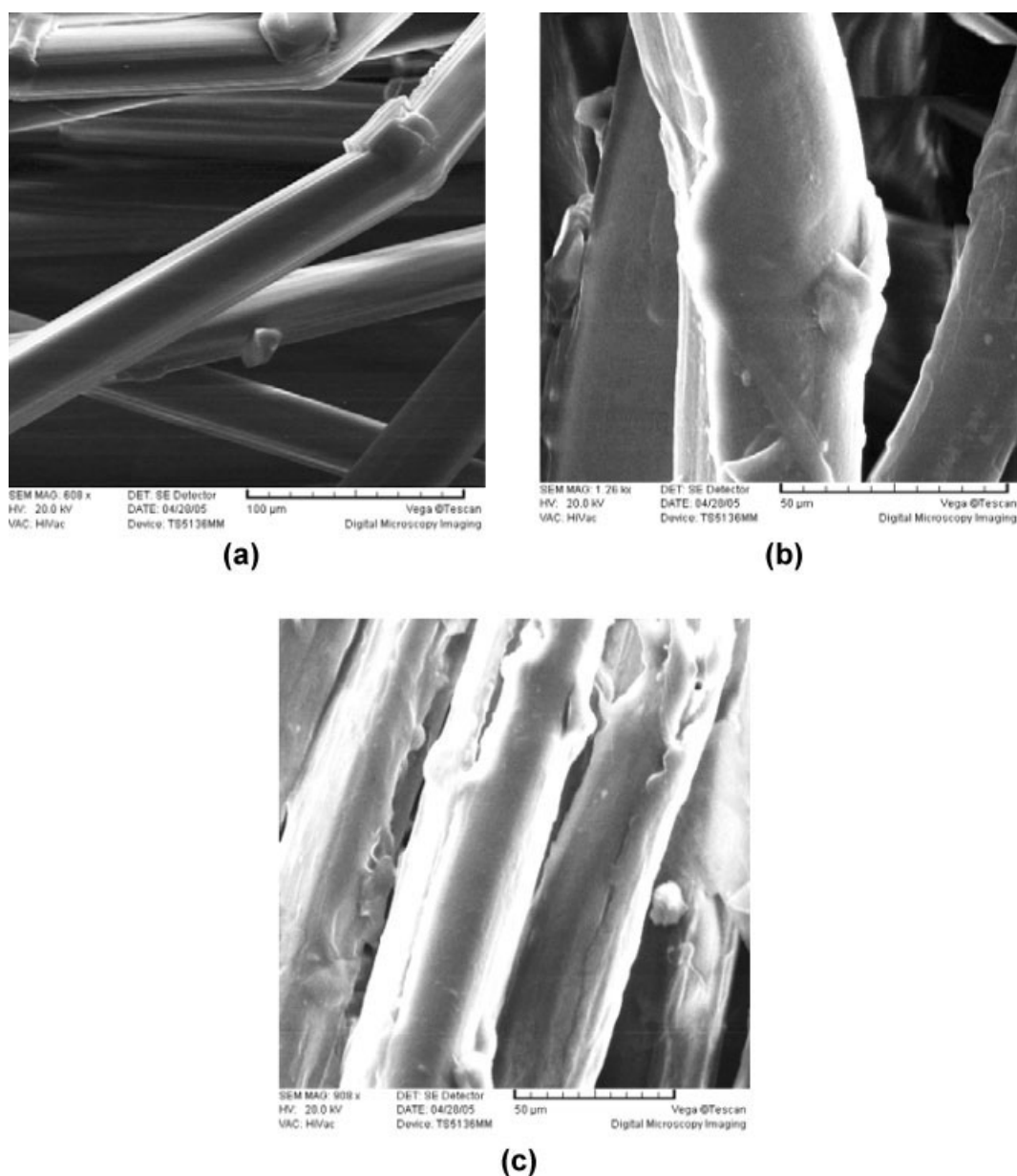


Figure 8 SEM images of various fiber fracture surfaces: (a) Original UHMWPE fiber/DGEBA, (b) chemically treated UHMWPE fiber/DGEBA, and (c) Plasma-treated UHMWPE fiber/DGEBA composites.

nearly identical to that of a aramid-fiber-reinforced DGEBA composite. This result suggests that the UHMWPE fiber is an excellent candidate for use as a

reinforcement material because of its high specific strength and lighter weight (0.97 g/cm^3) relative to that of aramid fibers (1.39 g/cm^3).

TABLE III
Mechanical Properties of Composites Formed from Various DGEBA Matrices

System	Fiber content (vol %)	Tensile modulus (GPa)	Tensile strength (MPa)	Elongation (%)
Untreated UHMWPE fiber/neat epoxy resin	36.6	8.6 ± 0.3	535.4 ± 8.4	20.8 ± 1.1
Untreated UHMWPE fiber/PU modified epoxy resin	36.0	9.6 ± 0.3	694.9 ± 11.4	21.3 ± 1.1
Untreated UHMWPE fiber/BHHBP-epoxy resin	36.9	11.1 ± 0.3	708.5 ± 11.9	21.4 ± 1.2
Plasma treated UHMWPE fiber/neat epoxy resin	37.9	8.7 ± 0.4	553.8 ± 9.1	12.8 ± 0.7
Plasma treated UHMWPE fiber/PU modified epoxy resin	37.5	9.8 ± 0.4	703.9 ± 11.6	13.9 ± 0.8
Plasma treated UHMWPE fiber/BHHBP-epoxy resin	38.0	11.6 ± 0.4	721.7 ± 11.9	15.0 ± 0.7
Kevlar fiber/neat epoxy resin	37.0	10.9 ± 0.2	524.4 ± 7.3	4.8 ± 0.4

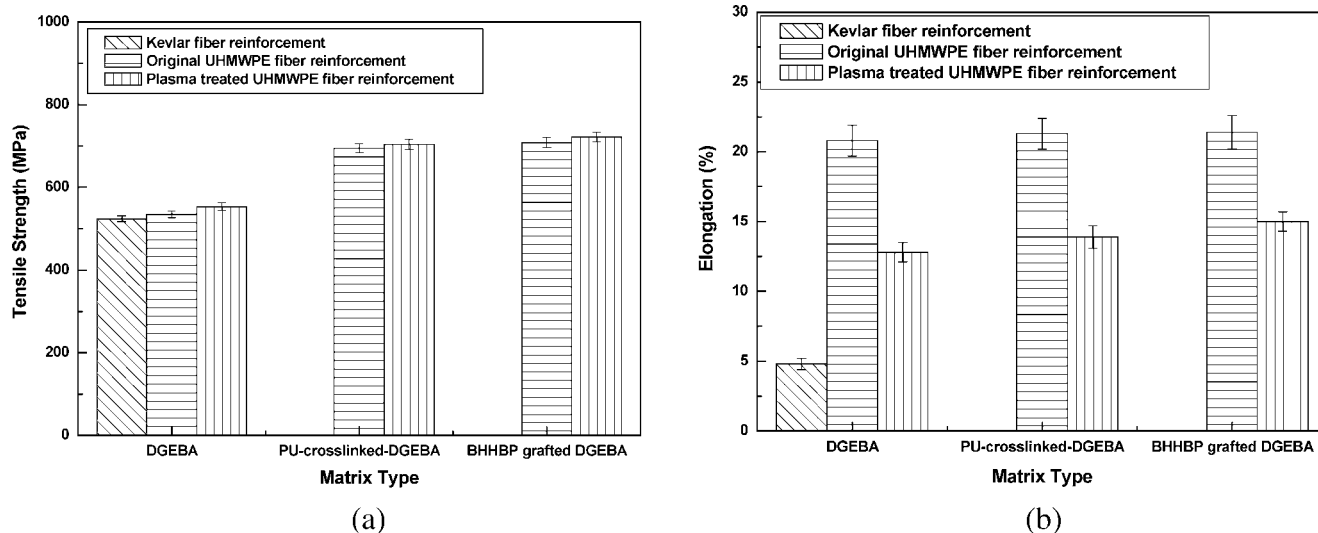


Figure 9 (a) Effects that the choices of fiber and matrix have on the tensile strengths of composites. (b) Effects that the choice of fiber and matrix have on the elongation of composites.

From the results listed in Table III and presented in Figure 9(b)—comparing composite systems formed from neat DGEBA and from the two modified DGEBA matrices—it appears that the choice of resin matrix did not significantly affect the elongation properties. The elongations of the untreated UHMWPE fiber-reinforced composites were all between 20.8 and 21.4% and those of the plasma-treated UHMWPE fiber-reinforced composites were all between 12.8 and 15.0%. The plasma-treated UHMWPE fiber-reinforced composites exhibited lower elongations relative to those of the original UHMWPE fiber-reinforced composites because of better interfacial adhesion between the UHMWPE fibers and the DGEBA matrix, as noted earlier from the results in Table II and the better wet-out properties suggested in Figures 8(a–c). Because of their ductility, the UHMWPE fiber-reinforced composites exhibited larger elongations (>10%) than did the aramid fiber-reinforced composite (4.8%).

CONCLUSIONS

Evidence obtained from ESCA, changes in weight, and SEM images suggest that plasma and chemical agent treatment improved the degree of interfacial adhesion between UHMWPE fibers and DGEBA matrices because of the introduction of micropits on the plasma-treated UHMWPE fiber surfaces and of rough, corrugated protuberances on the chemically treated UHMWPE fibers' surfaces.

The UHMWPE fiber-reinforced composites formed from both types of surface-modified UHMWPE exhibited slightly improved tensile strengths but notably decreased elongations relative to those of the untreated UHMWPE fiber-reinforced composite, as con-

firmed from SEM images of the fracture surfaces and from wet-out analyses.

From studies of composite systems formed from neat DGEBA and from two modified DGEBA matrices, it was found that the choice of resin matrix was an important factor affecting the tensile strength, but not the elongation. The increased tensile strengths of composites prepared from PU-crosslinked DGEBA and BHHBP-DGEBA matrices can be explained as resulting from (a) crosslinking between the soft PU prepolymer and the DGEBA matrix and (b) grafting between the rigid-rod-like BHHBP and the DGEBA matrix.

References

- Han, J. L.; Tseng, S. M.; Mai, J. H.; Hsieh, K. H. *Die Angew Makromol Chem* 1990, 182, 193.
- Han, J. L.; Tseng, S. M.; Mai, J. H.; Hsieh, K. H. *Die Angew Makromol Chem* 1991, 184, 89.
- Lin, J.-M.; Ma, C.-C. M.; Tai, N.-H.; Chang, W.-C.; Tsai, C.-C. *Polym Compos* 2000, 21, 305.
- Hung, A. Y. C.; Wang, F.-Y.; Yeh, S.-R.; Chen, W.-J.; Ma, C.-C. M. *J Appl Polym Sci* 2002, 84, 1609.
- Wu, H.-D.; Ma, C.-C. M.; Lin, J.-M. *J Appl Polym Sci* 1997, 63, 911.
- Ma, C.-C. M.; Lee, C.-T.; Wu, H.-D. *J Appl Polym Sci* 1998, 69, 1129.
- Ma, C.-C. M.; Tseng, H.-T.; Wu, H.-D. *J Appl Polym Sci* 1998, 69, 1119.
- Wang, F.-Y.; Ma, C.-C. M.; Wu, W.-J. *J Appl Polym Sci* 1999, 73, 881.
- Arnold, J. J.; Zamora, M. P.; Brennan, A. B. *Polym Compos* 1996, 17, 332.
- Pegoretti, A.; Ashkar, M.; Migliaresi, C.; Marom, G. *Compos Sci Technol* 2000, 60, 1181.
- Zheng, Z.; Tang, X.; Shi, M.; Zhou, G. *Polym Int* 2003, 52, 1833.
- Debnath, S.; Ranade, R.; Wunder, S. L.; Baran, G. R.; Zhang, J.; Fisher, E. R. *J Appl Polym Sci* 2005, 96, 1564.
- Silverstein, M. S.; Breuer, O. *Compos Sci Technol* 1993, 48, 151.

14. Moon, S. I.; Jang, J. *Compos Sci Technol* 1999, 59, 487.
15. Zhang, H.; Sui, M.; Zhang, J.; Wang, S. *J Appl Polym Sci* 2003, 89, 2757.
16. Brown, J. R.; Mathys, Z. *J Mater Sci* 1997, 32, 2599.
17. Knittel, D.; Kesting, W.; Schollmeyer, E. *Polym Int* 1997, 43, 231.
18. Wu, J.; Cheng, X. H. *Mech Compos Mater* 2005, 41, 181.
19. Cheng, X.-H.; Wu, J.; Xie, C.-Y. *J Appl Polym Sci* 2004, 92, 1037.
20. Stenhouse, P. J.; Valles, E. M.; Kantor, S. W.; Macknight, W. J. *Macromolecules* 1989, 22, 1467.
21. Zheng, Z.; Tang, X.; Shi, M.; Zhou, G. *J Polym Sci Part B: Polym Phys* 2004, 42, 463.
22. Shu, W.-Y.; Lin, K.-F. *Polym Compos* 1992, 13, 213.
23. Roylance, D.; Roylance, M. *Polym Eng Sci* 1978, 18, 249.
24. Ika, V. S.; Frisch, H. L.; Walters, G. R.; Painter, P. C.; Frisch, K. C. *J Polym Sci Polym Chem Ed* 1986, 24, 2297.