

Morphology, Thermal and Mechanical Properties of Glass Fiber-Reinforced Crosslinkable Poly(arylene ether nitrile)

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ABSTRACT: Crosslinkable poly(arylene ether nitrile)/glass fiber (PEN/GF) composites with high thermal stabilities and mechanical properties were prepared by a economically and environmentally viable method of melt extrusion and injection molding. The feasibility of using PEN/GF composites was investigated by evaluating its morphological, rheological, thermal, and mechanical properties. The morphology shows a good dispersion and strong interfacial interaction between PEN and GF. Thermal studies reveal that the thermal stabilities of PEN/GF are improved significantly with increase of GF content. Mechanical investigation manifested that GFs have strengthening effect (increase in flexural, tensile, and impact strength) on the mechanical performance of PEN composites. Most importantly, crosslinking reaction of PEN/GF composites can further improve their mechanical performances, because a couple of GFs are agglomerated by thermal motion and strong interfacial adhesion and the local agglomeration does not break the global uniform distribution. This work shows that both the enhancement of GF content and the crosslinking reaction of PEN/GF composites are two key factors influencing the thermal and mechanical properties. © 2012 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* 129: 130–137, 2013

KEYWORDS: crosslinking; thermal properties; mechanical properties

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INTRODUCTION

Poly(arylene ether nitrile) (PEN), one of the high-performance engineering thermoplastics, has been widely used in microelectronic industry, aerospace, electrical insulation, and semiconductor industries because of their outstanding properties such as high thermal stabilities, excellent mechanical and chemical inertia.^{1–7} However, compared with some thermosetting resin such as bisphthalonitrile, the thermal and mechanical properties of normal PEN are not high enough, and so its use and processing in high-performance applications are limited. Phthalonitrile-terminated PEN has been synthesized in our laboratory through the structure modification to PEN.⁸ The presence of phthalonitriles in PEN endows the polymers with strong polarizability, which promotes the adhesion of the polymers to many substances. Moreover, the phthalonitriles also serve as potential sites for the crosslinking reaction of PEN because the groups are likely to form thermally stable phthalocyanine rings.⁹ For industry applications, it is essential to develop multifunctional PEN composites, which possess high thermal stabilities and good mechanical properties.

An approach to reach this target is doping inorganic fillers, such as silicate,¹⁰ carbon fiber,¹¹ and clays,¹² into polymer matrix. Recently, there is interest to use glass fiber (GF) as fillers, due to high flexural, transverse, tensile and impact strength, high stiffness, low density and low thermal conductivity.¹³ Although many studies of GF composites have been reported,^{14–16} relatively few work has focused on GF blending with crosslinkable thermoplastic polymer. In our laboratory, the continuous GF-reinforced PEN composites have been studied,¹⁷ which also involved the crosslinking reaction of that PEN. However, this crosslinking reaction needs rigid reaction condition and complex process. The process of preparing PEN/GF composites has three steps, which included preparation of PEN films, prepregged glass fabrics, and hot pressing. Each step needs more than 8 h of processing time. What's worse, polarity and toxic solvent, such as *N*-Methyl-2-pyrrolidone, *N,N'*-dimethylformamide, was evaporated out. In addition, the reported PEN resins are very difficult to occur crosslinking reaction without the catalytic and high-temperature processing, due to the steric hindrance of the single pendant nitrile groups on benzene. Because of the reason, this advance of mechanical properties after crosslinking reaction was not obvious.

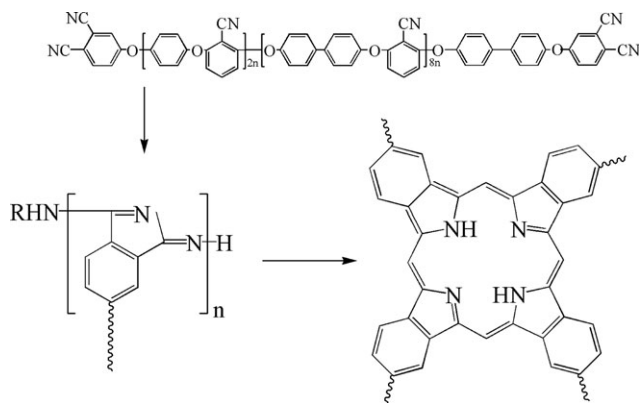


Figure 1. Proposed phthalonitrile oligomer reaction and subsequent network formation.

However, the PEN end-capped with phthalonitriles have higher reactivity than the pendant nitriles groups for crosslinking reaction, because the steric hindrance of phthalonitriles decreased. The PEN resins can be crosslinked without catalyst at relatively high temperature in 2 h.⁸ The presence of phthalonitriles in PEN endows the polymers with strong polarizability, which promotes the interfacial interaction of the polymers and GF.^{19–21} Hydrogen bonds were formed through phthalocyanines rings and Si—OH, which enhance dispersion and interfacial interaction of GF into PEN matrix.^{22,23} In addition, crosslinking reaction of PEN/GF composites in high temperature process further enhance interfacial interaction between PEN and GF, which can improve thermal and mechanical performances of composites.^{24–26} The improvement of thermal and mechanical properties of these networks is attributed to a high level of aromaticity and the proposed formation of heterocyclic crosslinks in the network (Figure 1).²⁷

Crosslinkable PEN/GF composites were prepared by the economically and environmentally viable melt-mixing method. The crosslinking reaction of PEN/GF composites improved dispersion and interfacial interactions of this system. Morphological, rheological, thermal and mechanical properties of PEN/GF composites were systematically investigated as a function of GF content. In addition, the effect of crosslinking reaction on the properties was investigated under the appropriate curing condition we have studied. This study was designed to evaluate the effect of increase of GF content and a curing behavior on some mechanical properties of PEN/GF composites.

EXPERIMENTAL

Materials

PEN has been synthesized in our laboratory.⁸ It is a copolymer derived from 2,6-difluorobenzonitrile with extra biphenyl (BP) and hydroquinone (HQ) (BP : HQ = 84 : 20 by mol) with inherent viscosity of 1.38 dL/g [by Ubbelohde viscosity method, at 25°C and with a concentration of 0.005 g/mL in *N*-methyl-2-pyrrolidinone (NMP)]. Commercially available chopped strand GFs have a diameter 13 μm, CTE $8.5 \times 10^{-6} 1/^\circ\text{C}$ and a Young modulus 72 GPa, which was purchased from Yancheng Xinhui, China.

Processing

The processing method in this study is melt-mixing because of its simplicity and compatibility with existing industrial polymer processing techniques such as extrusion and injection molding. To prepare the samples of the PEN/GF composites, the preparation processes included four steps. (1) Melt-mixing and granulation: GF-reinforced PEN blends (GF content: 0, 10, 20, 30, and 40 wt %, which mark as PEN, PEN/GF-1, PEN/GF-2, PEN/GF-3, and PEN/GF-4) were produced on a TSSJ-2S corotating twin-screw extruder (China Blue Star Chengrand Chemical Co., Chengdu, China) and the shear rate was 120 rpm/min. The temperature was maintained at 290, 300, 310, 320, 330, and 310°C from the hopper to the die. (2) Drying: the granulate was dried in condensation dryer at 100°C for 24 h after extrusion to reach a moisture content of about 0.05%. (3) Injection: the specimens were produced on an injection molding machine (Daca Micro Injector). The temperature was operated at 320°C and the injection pressure was 1.1 MPa and was held for 3 min. In this step, we obtained a part of samples (PEN/GF-1, PEN/GF-2, PEN/GF-3, and PEN/GF-4). (4) Heat preservation: the specimens of PEN/GF-4 cured at 320°C were produced on a mold at 320°C for 2 h. PEN/GF-4 (320°C) was obtained in this step. The standard molds designed for different experimental measurements were taken out after the hot-press was finished.

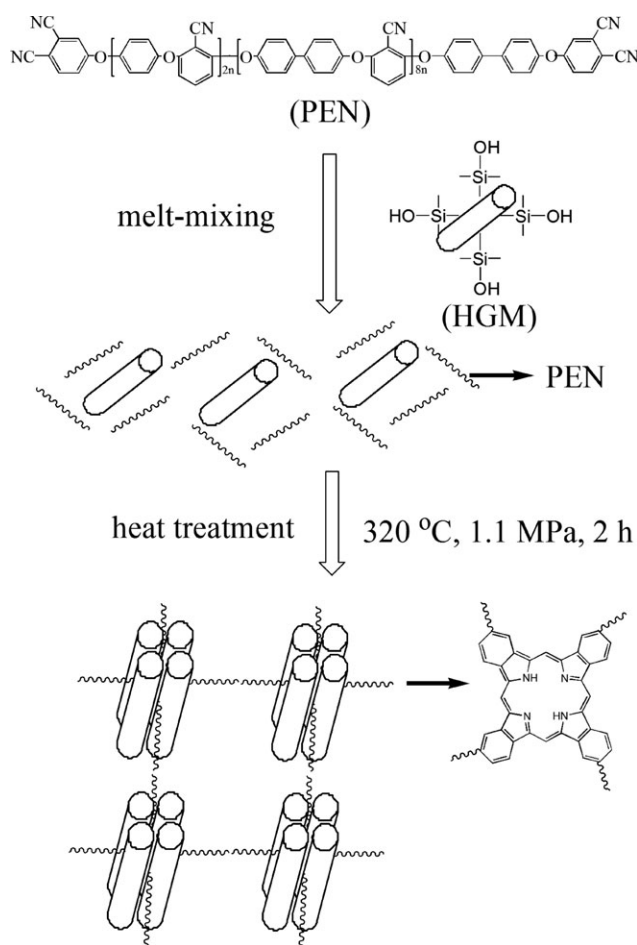


Figure 2. Preparation of PEN/GF composites.

Then, the molds were cooled to room temperature, and the specimens were obtained. Figure 2 shows the schematic cross-linking formation of phthalocyanines rings on PEN/GF composites.

Characterization Techniques

The polymer structure was analyzed by Fourier transform infrared spectroscopy (FTIR) spectra recorded on a Nicolet 200 SXV spectrophotometer in transmission mode.

The morphology of fracture surfaces of the PEN/GF composites were observed with a scanning electron microscope (JEOL JSM-5900LV). The SEM samples were coated with a thin layer of gold prior to examinations.

Differential scanning calorimetry (DSC) analyses of PEN/GF samples were performed on TA Instrument DSC Q100 modulated thermal analyzer under a nitrogen purge of $50 \text{ cm}^3 \text{ min}^{-1}$ at a heating rate $10^\circ\text{C min}^{-1}$ from room temperature to 350°C . Thermogravimetric analyses (TGA) of PEN/GF samples were performed on a TA Instruments TGA Q50 at a heating rate of $20^\circ\text{C min}^{-1}$ from room temperature to 900°C under nitrogen purge of $50 \text{ cm}^3 \text{ min}^{-1}$.

Dynamical rheological measurements were carried out on a rheometer (TA Instruments Rheometer AR-G2) equipped with a parallel plate geometry (25-mm diameter). Samples for rheometric measurements were prepared as a thickness of 1.0 mm and diameter of 25-mm round piece. The frequency sweep from 0.1 to 100 rad/s was performed at 320°C under dry nitrogen condition. For all the measurement, the PEN/GF samples were tested within the linear viscoelastic strain range.

Tensile (dog-bone type) and flexural tests (three-point bending mode) were performed with a SANS CMT6104 series desktop electromechanical universal testing machine (Shenzhen, China). The moving speed of the crosshead was 5 mm/min. Impact resistance tests (Izod type) were carried out following the ASTM D256 standard test method. All tests undergone at room temperatures and the reported values were calculated as averages of five specimens for each PEN/GF composite.

RESULTS AND DISCUSSION

IR spectra of the PEN and PEN/GF

Figure 3 shows the IR reflectance spectra of the PEN and PEN/GF composites. As the representative examples, from the IR reflectance spectra of the PEN and PEN/GF composite, absorption band at 2230 cm^{-1} represents $-\text{CN}$. Compared with PEN, the characteristic stretching band of $-\text{CN}$ weaken after doping GFs. An absorption band at about 1400 cm^{-1} represents the symmetric stretching of $\text{Si}-\text{O}-\text{Si}$ in PEN/GF composites. Three absorption bands emerged at 3400 cm^{-1} , 1600 cm^{-1} , and 1490 cm^{-1} , which are assigned to $-\text{NH}_2$, $-\text{NH}-$, and $-\text{C}=\text{N}-$, respectively. The existence of phthalocyanine rings is indicated. The results showed a good dispersion and strong interfacial interaction between PEN and GF.

Morphology

Figure 4(a) shows that GF was homogeneously dispersed in the PEN matrices. Figure 4(b) reveals that one GF was tightly adhered by PEN resins while another GF was inlaid inside ma-

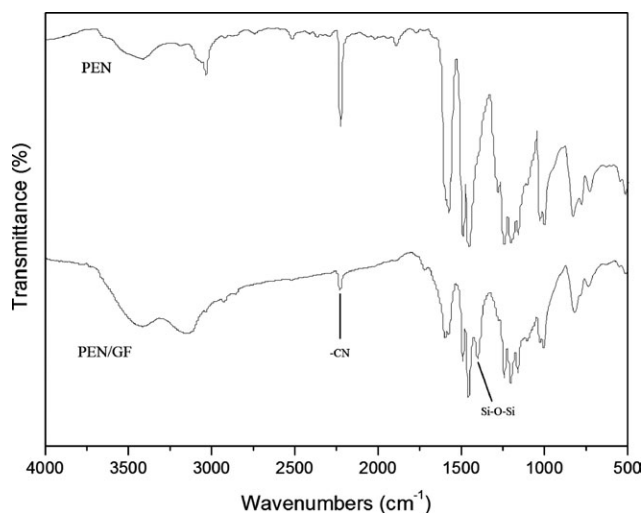


Figure 3. FTIR reflectance spectra of the PEN and PEN/GF-4.

trix. This simple interfacial adhesion between PEN and GF is just physical connection that can be broken easily, and thus the surface of PEN is smooth. The fracture morphology of PEN/GF-1 composite cured at 320°C exhibited that PEN matrix showed torn grain in the process of tearing, and the fracture mechanism is crosslinking of phthalocyanines rings⁹ [Figure 4(c)]. The surface coverage of the PEN on GF becomes coarse [Figure 4(d)], indicating the improvement of adhesive attraction between PEN and GF. It can be seen from the phenomenon that torn grain of PEN resin on GF surface that the adhesion attraction between GF and PEN matrix became strong. This is attributed to self-crosslinking of PEN and linkage of phthalocyanines and $\text{Si}-\text{OH}$, which will enhance physical and chemical interactions between PEN and GF. As can be seen, GF is homogeneously dispersed in PEN matrix, but not all GFs are free-standing in the 40 wt % GF-filled composite [Figure 4(e)]. It is clear that some GFs are partially agglomerated by interfacial interaction of PEN [Figure 4(f)]. In addition, GF is apparently agglomerated and packed by more PEN resin after PEN/GF-4 composite cured at 320°C [Figure 4(g,h)]. This apparent agglomeration with strong adhesive attraction will finally improve the mechanical properties of PEN/GF composites, since that one GF is easy to be broken while a bunch of GFs are difficult to be broken. The small-scale agglomeration and strong interfacial adhesion will be beneficial to the final mechanical properties.

Rheological Properties

The complex viscosities, $|\eta^*|$, of the PEN/GF composites are shown in Figure 5. The PEN materials exhibits a strong shear thinning effect, but the neat PEN and PEN/GF-1 in this study show a small frequency dependence. The complex viscosity increases with the increase of GF content. The effect of the GF is the most notable at low frequencies and decreases with increasing frequency due to shear thinning. This result is in accordance with theoretical expectation and experimental observation for fiber-reinforced composites.¹⁶ It is note that the complex viscosity curves for PEN/GF-1 have similar frequency dependencies to the pure PEN, revealing a Newtonian plateau

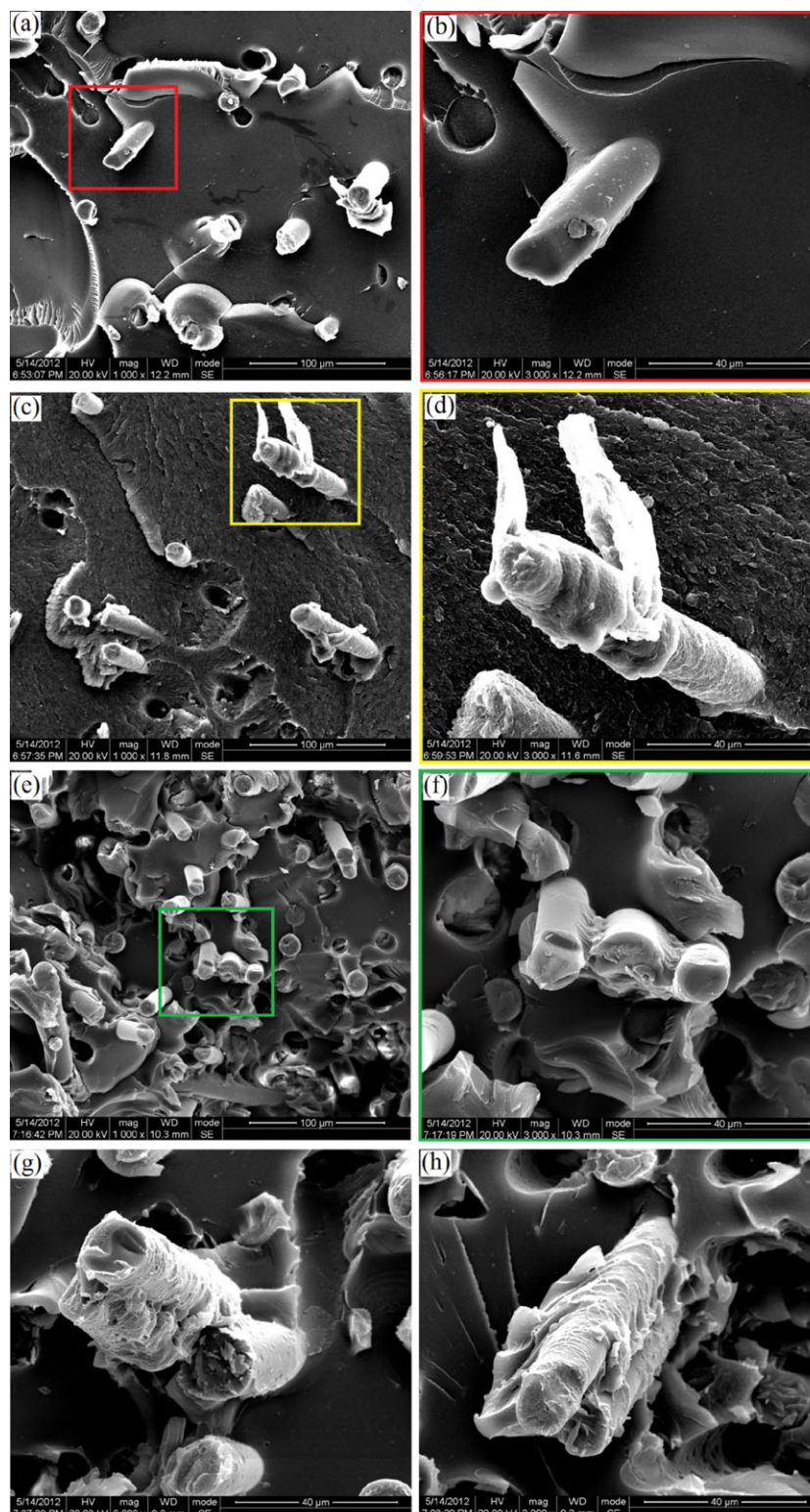


Figure 4. (a) Cross-sectional SEM image of PEN/GF-1, showing its tensile section structure. (b) Magnified image of one section of (a). (c) Cross-sectional SEM image of PEN/GF-1. (d) Magnified image of one section of (c). (e) Cross-sectional SEM image of PEN/GF-4, showing its tensile section structure. (f) Magnified image of one section of (e). (g, h) Magnified images of a section of PEN/GF-4. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

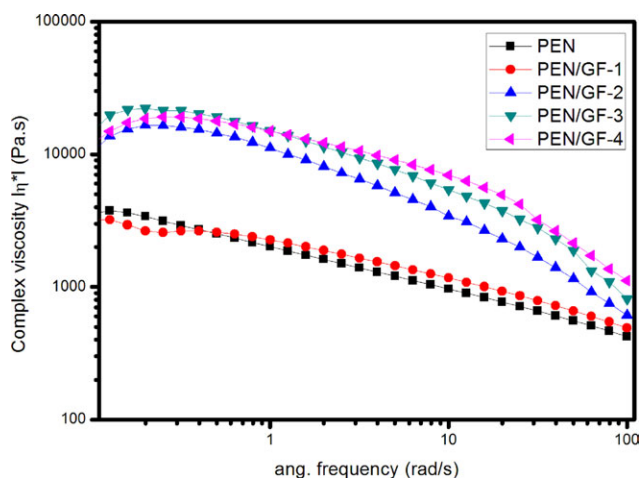


Figure 5. Complex viscosity of different content GF filled PEN. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

at low frequencies. However, the complex viscosity curves have a slope for PEN/GF-2, PEN/GF-3, and PEN/GF-4. The three curves are similar at low frequencies (frequency is less than 1 rad/s), which is due to agglomeration of GF reducing the effect of complex viscosity. This result can be explained that the agglomeration of GF equivalently increases the diameter of fillers, but the number does not change a lot. However, it is found that the complex viscosity increases with the increase of GF content at high frequency (frequency is greater than 1 rad/s), because the agglomeration is broken by intense shearing.

Figures 6 and 7 show the dynamic storage modulus (G') and loss modulus (G'') for the composites. The storage modulus and loss modulus increase with the increase of frequency. The values of storage modulus G' and loss modulus G'' for PEN/GF-1 have similar frequency dependencies as the neat PEN. The values of storage modulus G' and loss modulus G'' for PEN/GF-2, PEN/GF-3, and PEN/GF-4 have an advance, which are similar

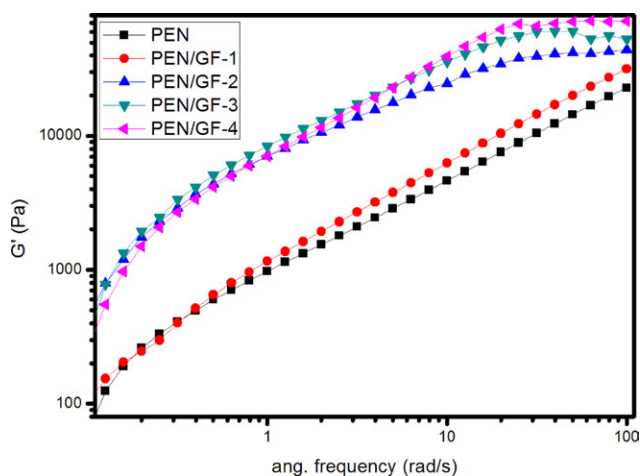


Figure 6. Storage modulus G' of different content GF filled PEN. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

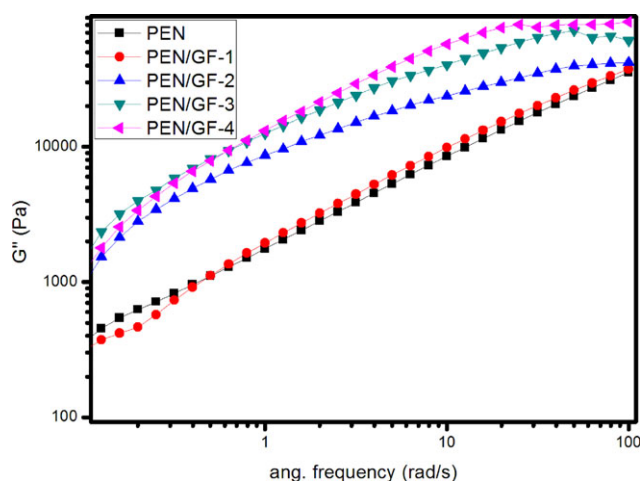


Figure 7. Loss modulus G'' of different GF content filled PEN. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

as to the trend of complex viscosity at low frequencies. However, the curves have changed at 10 rad/s for storage modulus G' , while it has changed at 1 rad/s for loss modulus G'' . Since, the effect of frequency on the PEN/GF composites is more sensitively reflected on the storage modulus G' than the loss modulus G'' . A rapid increase in modulus of the composites between 10 and 20 wt % GFs can be clearly identified. This phenomenon can be related to a rheological percolation transition at which the GFs restrict the motion of the polymer matrix. At low GF contents, such filler particles alter the local mobility of individual chains only.²⁸ These localized restrictions begin to interact across the sample volume at the percolation threshold, leading to the change in modulus. In order to obtain a detailed insight into the rheological percolation value of the composites, a power-law relation can be used here to determine the threshold of the rheological percolation²⁹:

$$G' \propto (m - m_c)^\beta \quad (1)$$

where m is the GF weight fraction, m_c is the rheological percolation threshold, and β is the critical exponent ($m_c = 0.85\%$, $\beta = 1.67$).

Thermal Properties

DSC and TGA curves are plotted in Figures 8 and 9 to show the effect of GF content on thermal properties of PEN/GF composites. The T_g data with different GF contents were shown in Table 1. As we can see, the T_g values of PEN/GF composites are higher than that of pure PEN polymer. T_g goes up after the addition of GFs and is increased by 10°C when GF content is 40 wt %. These effects may be caused by the interaction of PEN chains and GFs. The thermal stability of PEN/GF composites are evaluated by 5% weight loss temperatures ($T_{5\%}$ s) and char yields (C_s s) at 900°C. The $T_{5\%}$ s of PEN/GF composites increase with the increase of GF content, which shows a good thermal stability with $T_{5\%}$ in the range from 508 to 519°C. In addition, the C_s s of PEN/GF composites apparently increased with increase of GF content. Compared with pure PEN, the C_s s of

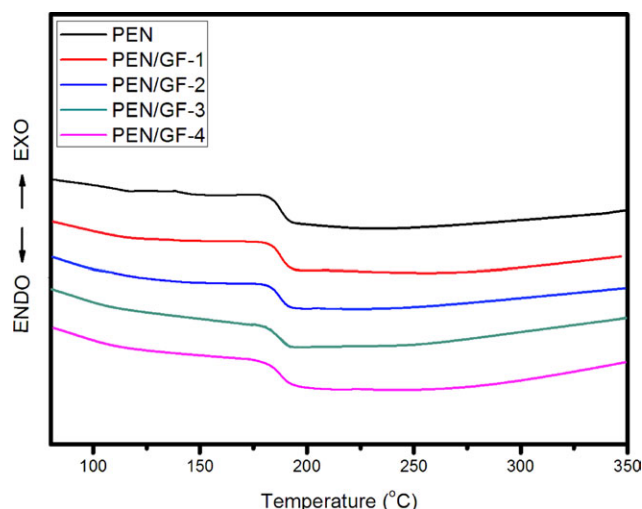


Figure 8. DSC curves of PEN/GF composites. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

PEN/GF-1, PEN/GF-2, PEN/GF-3, and PEN/GF-4 composites are increase by 62, 67, 71, 75, and 77%, respectively. These results may be attributed to the intrinsic merits of GF such as the special thermal stabilities and nice barrier effect.³⁰ In addition, they are mainly due to uniform dispersion states and good compatibility. From thermal studies, the addition of GF significantly improves the thermal stabilities of PEN/GF composites.

Mechanical Properties

The flexural strength of PEN/GF composites is shown in Figure 10. It can be seen that flexural strength increases with increasing GF loading. Compared with the neat PEN, PEN/GF-4 composite shows a flexural strength as high as 208 MPa, which is increased by about 200%. The improvement in the flexural strength can be attributed to uniform distribution and strong interfacial adhesion between GF and the PEN matrix, as confirmed by SEM images in Figure 2. Interestingly, it is noted that the flexural strength of PEN/GF-4 cured at 320°C increases to

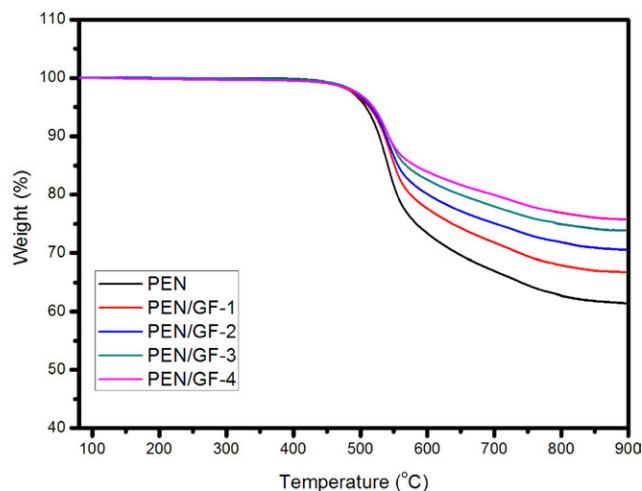


Figure 9. TGA curves of PEN/GF composites. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table I. T_g s of the Composites

Sample	T_g (°C)
PEN	182 ± 1
PEN/GF-1	184 ± 1
PEN/GF-2	185 ± 1
PEN/GF-3	187 ± 1
PEN/GF-4	191 ± 1

about 280 MPa, which is promoted by crosslinking reaction. This result confirms the hypothesis of morphology analysis that the agglomeration of a couple of GF with strong adhesive attraction will improve mechanical properties of PEN/GF composites. Each freestanding GF inlays the PEN matrix before crosslinking reaction, whereas a couple of GF is agglomerated by thermal motion and strong interfacial adhesion through crosslinking reaction. The flexural strength of PEN/GF-4 cured at 320°C improved because of the crosslinking between GF and matrix polymer. All results indicate that the enhancement of GF content and the crosslinking reaction largely improves the flexural properties of PEN/GF composites.

The analysis of tensile and impact properties is the same as that of the flexural property. The tensile strength data of PEN/GF composites are shown in Figure 11. It can be seen that tensile strength increases with the increase of GF content. Compared with the tensile strength of pure PEN (30 MPa), the tensile strength of PEN/GF-1, PEN/GF-2, PEN/GF-3, and PEN/GF-4 composites improve to 33, 43, 116, and 132 MPa, respectively. The improvement in the tensile strength can be attributed to uniform distribution and strong interfacial adhesion between GF and the PEN matrix. It is noted that the tensile strength of PEN/GF-4 cured at 320°C increases to about 165 MPa. Figure 12 shows the impact strength of PEN/GF composites. Compared with the impact strength of the neat PEN, the impact strength of PEN/GF-1, PEN/GF-2, PEN/GF-3, PEN/GF-4, and PEN/GF-4 cured at 320°C composites increase by 0.4, 4, 6, 8, and 11 J/m².

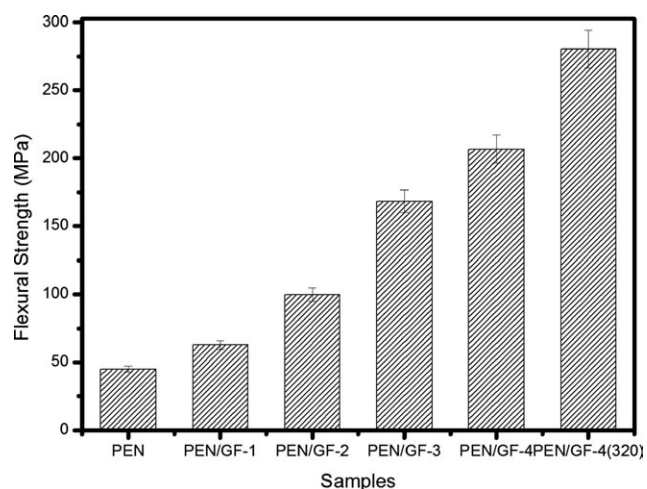


Figure 10. Flexural strength of different content GF filled PEN and PEN/GF-4 cured at 320°C.

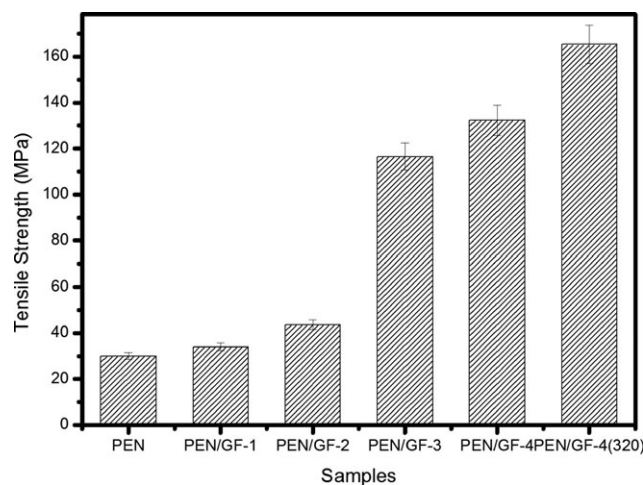


Figure 11. Tensile strength of different content GF filled PEN and PEN/GF-4 cured at 320°C.

As a result, the mechanical properties are improved obviously by the increase of GF content. More importantly, the mechanical properties of PEN/GF composites are enhanced by crosslinking reaction of PEN/GF system under the appropriate curing condition.

The flexural strength, tensile strength, and impact strength of composites are listed in Table II. It can be seen clearly, the flexural strength, tensile strength, and impact strength improved gradually with the increase of GF content. The flexural strength, tensile strength, and impact strength of PEN/GF-4 enhanced after curing reaction at 320°C. Thus, the mechanical properties are improved obviously by the increase of GF content and curing reaction at 320°C for 2 h. The significant improvements in the flexural strength, tensile strength are due to the reaction of phthalonitriles, and crosslinked phthalocyanines rings network through heat treatment. The matrix PEN and GFs get a stronger interfacial adhesion, which increases the mechanical properties of composites.

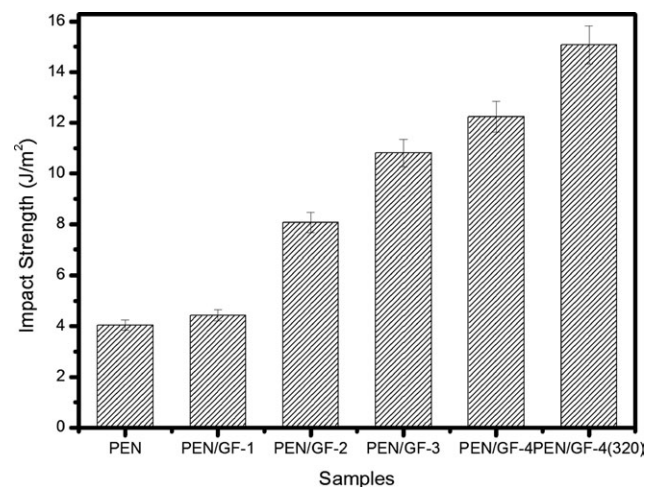


Figure 12. Impact strength of different content GF filled PEN and PEN/GF-4 cured at 320°C.

Table II. Mechanical Properties of the Composites

Sample	Flexural strength (MPa)	Tensile strength (MPa)	Impact strength (MPa)
PEN	45 ± 2	30 ± 2	4 ± 1
PEN/GF-1	62 ± 2	33 ± 2	4 ± 1
PEN/GF-2	99 ± 3	43 ± 2	8 ± 1
PEN/GF-3	168 ± 4	116 ± 4	10 ± 1
PEN/GF-4	206 ± 5	132 ± 4	12 ± 1
PEN/GF-4 (320)	280 ± 5	165 ± 4	15 ± 1

CONCLUSIONS

In summary, GF-reinforced crosslinkable PEN composites are prepared by an economically and environmentally viable method of melt extrusion and injection molding. The PEN/GF composites are investigated by evaluating the thermal, rheological and mechanical properties and studying the morphology of this system as a function of GF content. In addition, the mechanical properties are effectively improved through a simple crosslinking reaction under a appropriate curing temperature we have studied. As the content of GF increased, the thermal and mechanical properties are greatly enhanced. The $T_{5\%}$ and C_y increases from 508 to 519°C and 63 to 77%, respectively. More importantly, the mechanical properties are improved a lot: (1) flexural strength increases by 160 MPa; (2) tensile strength increases by 102 MPa; (3) impact strength increases by 8 J/m². What's more, the flexural, tensile and impact strength enhance to 280 MPa, 165 MPa, and 15 J/m², respectively, via crosslinking at 320°C. The development of mechanical properties is explained by analysis of SEM images, which show that each freestanding GF inlays the PEN matrix before crosslinking reaction, whereas a couple of GFs are agglomerated by thermal motion and strong interfacial adhesion through crosslinking reaction. In addition, it is noted that the local agglomeration doesn't break the global uniform distribution. As a result, the agglomeration without breaking the uniform distribution of a couple of GF with strong adhesive attraction will improve mechanical properties of PEN/GF composites. We believed that these enhanced performances will make the PEN/GF composites attractive for some critical circumstances required applications. In addition, the advance of mechanical properties of PEN/GF composites did not bring the cost increase.

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REFERENCES

- Verborgt, J.; Marvel, C. S. *Polym. Sci. Polym. Chem. Ed.* **1973**, *11*, 261.
- Saxena, A.; Sadhana, R.; Rao, V. L.; Kanakavel, M.; Ninan, K. N. *Polym. Bull.* **2003**, *50*, 219.

3. Rao, V. L.; Saxena, A.; Ninan, K. N. *Macromol. Sci.: Polym. R* **2002**, *42*, 513.
4. Heath, D. R.; Wirth, J. G. U.S. Pat.3,730,946 (1973).
5. Keller, T. M. *J. Polym. Sci. Part A: Polym. Chem.* **1988**, *26*, 3199.
6. Keller, T. M. *Polymer* **1993**, *34*, 952.
7. Keller, T. M.; Dominguez, D. D. *Polymer* **2005**, *46*, 4614.
8. Zou, Y.; Yang, J.; Zhan, Y.; Yang, X.; Zhong, J.; Zhao, R.; Liu, X. *J. Appl. Polym. Sci.* **2012**, *125*, 3829.
9. Du, R. H.; Li, W. T.; Liu, X. B. *J. Polym. Degrad. Stabil.* **2009**, *94*, 2182.
10. Giannelis, E. P. *Adv. Mater.* **1996**, *8*, 29.
11. Kiliaris, P.; Papaspyrides, C. D. *Prog. Polym. Sci.* **2010**, *35*, 902.
12. Shen, J. W.; Chen, X. M.; Huang, W. Y. *J. Appl. Polym. Sci.* **2003**, *88*, 1864.
13. Park, S.; Jin, E.; Lee C. *Mater. Sci. Eng. A: Struct.* **2005**, *402*, 335.
14. Lee, J.; Yee, A. *Polymer* **2000**, *41*, 8363.
15. Lee, J.; Yee, A. *Polymer* **2000**, *41*, 8375.
16. Aous, A. A.; Timo, O. N.; Pekka, K. V.; Lippo, V. L. *Dent. Mater.* **2011**, *27*, 313.
17. Yang, J.; Zhong, J. C.; Zhao, R.; Liu, X. B. *J. Compos. Mater.* **2011**, *45*, 2587.
18. Meng, F. B.; Zhong, J. C.; Chen, Y. W.; Liu, X. B. *J. Appl. Polym. Sci.* **2011**, *120*, 1822.
19. Haddad, I.; Hurley, S. C.; Marvel, S. J. *Polym. Sci. Part A: Polym. Chem.* **1973**, *11*, 2793.
20. Anderson, D. R.; John, M. H. *J. Polym. Sci. Part A: Polym. Chem.* **1966**, *4*, 1689.
21. Sivaramakrishnan, K. P.; Samyn, C.; Westerman, I. J.; Wong, D. T. *J. Polym. Sci. Part A: Polym. Chem.* **1975**, *13*, 1083.
22. Chang, D. M.; Marvel, C. S. *J. Polym. Sci. Part A: Polym. Chem.* **1975**, *13*, 2507.
23. Ates, S.; Dizman, C.; Aydogan, B.; Kiskan, B.; Torun, L.; Yagci, Y. *Polymer* **2011**, *52*, 1054.
24. Yu, G. P.; Liu, C.; Wang, J. Y.; Li, G. H.; Han, Y. J.; Jian, X. G. *Polymer* **2010**, *51*, 100.
25. Yu, G. P.; Liu, C.; Wang, J. Y.; Gu, T. S.; Jian, X. G. *J. Polym. Degrad. Stabil.* **2009**, *94*, 1053.
26. Li, G. H.; Wang, J. Y.; Yu, G. P.; Jian, X. G.; Wang, L. H.; Zhao, M. S. *Polymer* **2010**, *51*, 1524.
27. Sumner, M. J.; Sankarapandian, M.; McGrath, J. E.; Riffle, J. S.; Sorathia, U. *Polymer* **2002**, *43*, 5069.
28. Sandler, J.; Broza, G.; Nolte, M.; Schulte, K.; Lam Y. M.; Shaffer, S. P. *Macromol. Sci. B* **2003**, *42*, 479.
29. Du, F. M.; Scogna, R. C.; Zhou, W.; Brand, S.; Fischer, J. E.; Winey, K. I. *Macromolecules* **2004**, *37*, 9048.
30. Yoo, Y.; Spencer, M. W.; Paul, D. R. *Polymer* **2011**, *52*, 180.