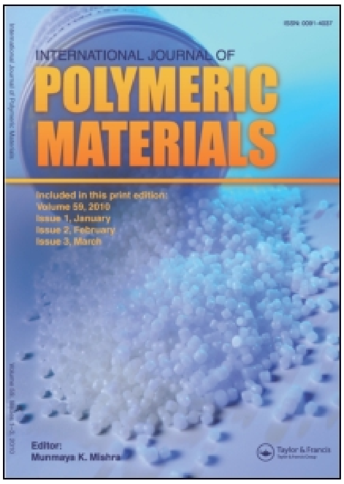

International Journal of Polymeric Materials
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713647664

Tensile Properties and Fracture Behaviour of Polycarbonate/PAN-based Carbon Fiber Composite

A. M. Zihlif[a]; V. Dl Liello[b]; E. Martuscelli[b]; G. Ragosta[b]
[a] Physics Department, University of Jordan, Amman, Jordan [b] Institute of Polymer Technology, Naples, Italy

To cite this Article Zihlif, A. M. , Liello, V. Dl , Martuscelli, E. and Ragosta, G.(1995) 'Tensile Properties and Fracture Behaviour of Polycarbonate/PAN-based Carbon Fiber Composite', International Journal of Polymeric Materials, 29: 3, 211 — 220

To link to this Article: DOI: 10.1080/00914039508012115

URL: http://dx.doi.org/10.1080/00914039508012115

Intern. J. Polymeric Mater., 1995, Vol. 29, pp. 211–220
Reprints available directly from the publisher
Photocopying permitted by license only

Tensile Properties and Fracture Behaviour of Polycarbonate/PAN-based Carbon Fiber Composite

A. M. ZIHLIF*
Physics Department, University of Jordan, Amman, Jordan

and

V. DI LIELLO, E. MARTUSCELLI and G. RAGOSTA
Institute of Polymer Technology, C.N.R. Via Toiano, 6 80072 Arco Felice, Naples, Italy

(Received February 9, 1995)

Yielding and fracture properties of polycarbonate composites reinforced with PAN-based carbon fibers are studied at different filler contents over a range of temperatures and strain rates. Tensile elastic modulus and the yield stress showed increase with increasing the filler concentration. The tensile yield stress of this composite showed temperature and strain rate dependence. Activation stress volume and activation energy of yielding process are determined using the Eyring-rate theory. The measured fracture toughness parameters *Gc* and *Kc*, are also enhanced with the filler content. The variations of the measured physical quantities are discussed in terms of the observed composite morphology.

KEY WORDS Polycarbonate, PAN carbon fibers, composite, yielding, fracture, toughness, morphology.

1. INTRODUCTION

Advanced polymer composites are receiving nowdays increasing interest since some of them have high mechanical and electrical performance as replacements for metals in specific areas of construction and aerospace applications. One method to develop these polymer composites is to add rather large amounts of conductive species as metallic fillers, carbon black, and carbon fibers. The conduction mechanism takes place in these reinforced polymers is based in general on the concept of creating conductive paths in the composites bulk. The technology of polymer-base composite components is now considered as crucial necessity for most industrial aspects. The ultimate mechanical properties of a polymeric composite may be strongly influenced by the degree of interfacial interaction between the filler and the matrix. Thus the

---

*To whom all correspondences should be addressed.

behaviour of a fiber-reinforced polymers is governed to a certain degree by the properties of the reinforcing fibers, resin matrix, and the efficiency of the matrix-fiber interface. Considerable research and technological efforts have been devoted in the last two decades to develop advanced composites materials and improve their physical reinforcement through modification of the used matrix resins and fillers.[1–4] For the purpose of investigation the electrical conductivity enhancement and mechanical performance a polymer composite of polycarbonate and PAN-based carbon fibers was chosen since we are already involved with the mechanical and electrical properties of PAN-based carbon fibers.[5] Actually, this article is one part of a series studies concerned with the mechanical and electrical behaviour of reinforced thermosets and thermoplastic composites.[6–7] In a recent paper,[8] we reported the results of a study concerning with some electrical properties of polycarbonate/PAN-based carbon fiber composite through impedance measurements. The observed dielectric constant and the electrical conductivity showed filler concentration, frequency, and temperature dependence attributed to tunneling and polarization effects. In the present study we report the tensile mechanical properties and fracture behaviour of this composite at different temperatures and strain rates in addition to a study on the observed composites morphology.

2. EXPERIMENTAL DETAILS

2.1 Materials and Composite Preparation

The materials used in this study are polycarbonate and PAN-based carbon fibers. Polycarbonate is commonly used as a matrix in reinforcing composite because it exhibit high impact strength, good electrical properties, low coefficient of thermal expansion, low water absorption coefficient, and high dimensional stability. The PAN-based carbon fibers are designed with high modulus and strength, good electrical conductivity and high thermal stability: They have average measured diameter 7 μm and provided from Celaneese company in USA inform of stands of 6000 fibers. Carbon fibers were chopped into single filaments of average length 1 mm and mixed with polycarbonate resin using a brabender-like apparatus (Rheocord EC of Haake Inc.) at temperature of 260°C with a mixing time of 10 minutes and at a roller speed of 32 r.p.m. The composites coming from the mixer were then compression molded in a heated press at a temperature of 260°C and a pressure of 100 Bar, to obtain sheets of 1.3 mm thick. The carbon fiber contents in these composites were 5, 10, 18 and 30 wt%.

2.2 Tensile Tests

To study the deformation behavior of these composite materials, dumb-bell shaped specimens were cut from the sheets. Tensile tests were performed by means of an Instron testing machine equipped with an environmental chamber for work at different temperatures and over a range of strain rates. Temperature readings were taken by placing a thermometer near the test specimen. Prior to testing the test specimens were dried under vacuum at 90°C for 10 hours.

2.3 Impact Fracture Tests

Fracture tests were carried out on a charpy Instrument Pendulum (Ceast Autographic Pendulum MK2) at an impact speed of 1 m/sec. Sample with a notch depth to width ratio of 0.3 and a test span of 48 mm were fractured at room temperature for all composite concentrations. The relative curves of energy and load against time as displacement were recorded at each temperature.

2.4 Microscopy and X-ray Diffraction

Adhesion and morphological investigations were carried out using a Philips 501 SEM on fracture surfaces obtained by tensile and impact tests. The samples for SEM observations were metal-coated using a Polaron sputtering apparatus with Au-Pd alloy. Optical examinations were carried out using a Wild M420 Stereomicroscope. The obtained X-ray diffraction patterns from the polycarbonate matrix were concentric rings indicating isotropy. Thus no orientation of the matrix takes place during compression moldings.

3. RESULTS AND DISCUSSION

3.1 Tensile Results

The stress-strain curves obtained at a strain rate $\dot{\varepsilon} = 7.4 \times 10^{-3}\ S^{-1}$ for various prepared composites show a ductile plastic deformation behavior. It was noticed that by increasing the content of the PAN-based carbon fibers, the degree of

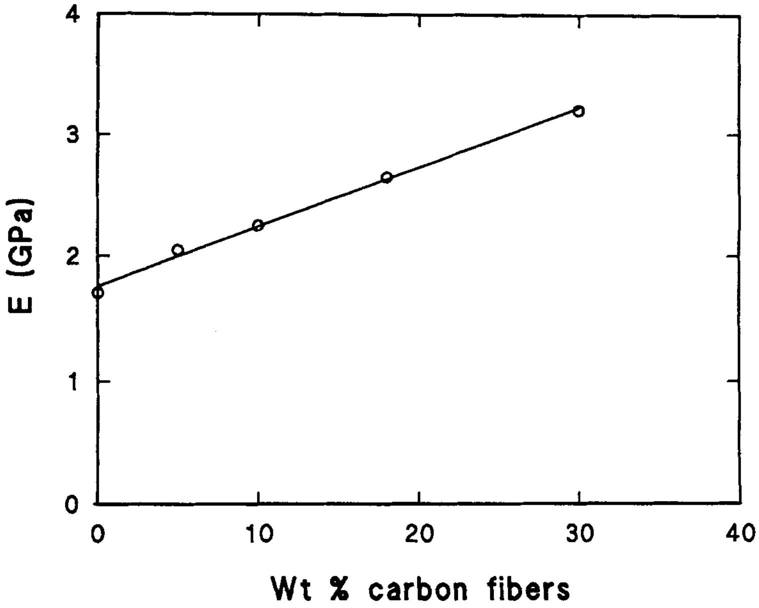

FIGURE 1 Tensile Young modulus of polycarbonate composite as a function of PAN-based carbon concentration, $\dot{\varepsilon} = 76 \times 10^{-3}$.

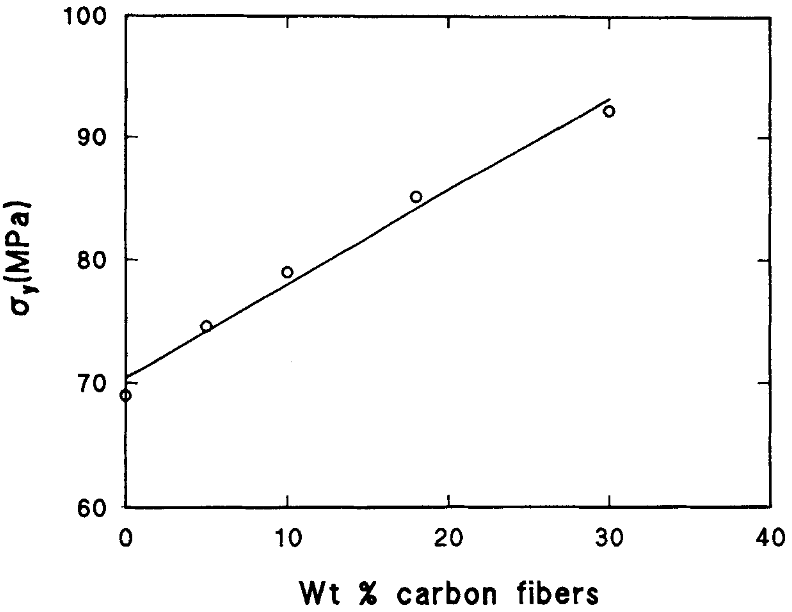

FIGURE 2 Tensile yield stress as a function of carbon fiber concentration, $\dot{\varepsilon} = 76 \times 10^{-3}$.

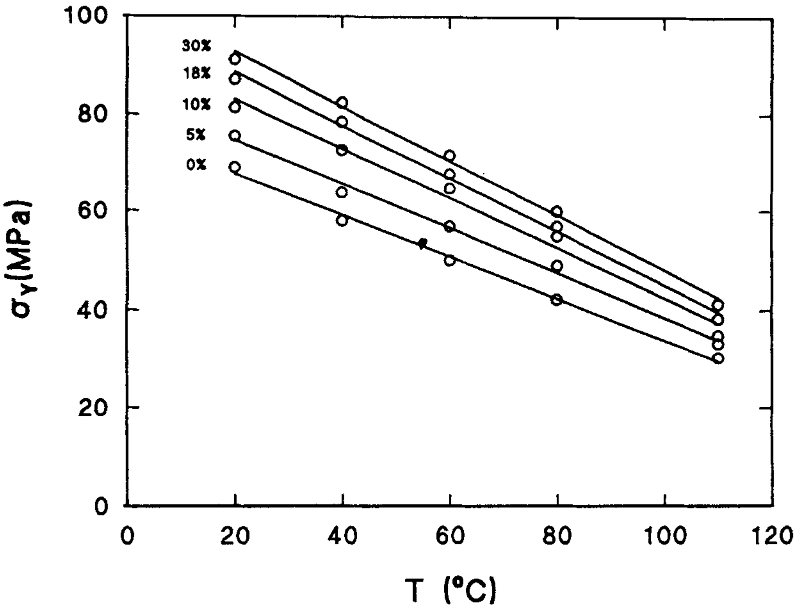

FIGURE 3 Tensile yield stress as a function of temperature.

brittleness increases. This is accounted for by the presence of relatively brittle carbon fibers embedded in a ductile polycarbonate matrix. The dependence of the Young's modulus (E) on the fiber concentration in composites is shown in Figure 1. It can be seen that the stiffness of the material increases linearly with the weight

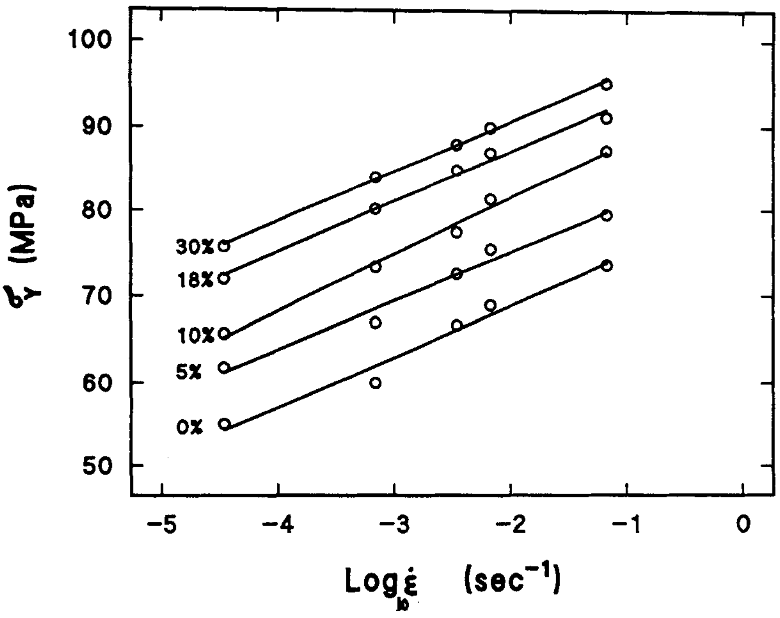

FIGURE 4 Dependence of the yield stress on strain rate.

fraction of the carbon fibers. This modulus enhancement is normally expected for reinforcing-fiber composites. The yield stress was determined from the intersection of two tangents on the stress-strain curve for a ductile behavior and from the maximum point for the brittle one.[9] Figure 2 shows the variations of the yield stress (σ_y) as a function of the carbon fiber content. This quantity increases linearly with filler content due to the strong interfacial bonding of the fibers with the polycarbonate matrix.

Stress-strain curves were also obtained at different temperatures and strain rates. The tensile yield stress for pure polycarbonate, and 5, 10, 18, 30 wt% fiber composites measured over a temperature to 110°C are shown in Figure 3. It was found that the yield stress decreases also linearly with temperature. The tensile yield stress for composite specimens measured at room temperature is plotted as a function of log strain rate in Figure 4. The data show a linear relationship between the yield stress and the strain rate for polymer and the composites, but the straight lines are not exactly parallel which indicates the occurrence of more than a single activated-rate process. This departure from parallelity is accounted for by the existence of the PAN carbon fibers. However, the data still show that the yield stress increases as a function of strain rate for the given composite. The equivalence in increasing the yield stress by increasing strain rate and decreasing temperature can be drawn from Figures 3 and 4. The overall effect of the strain rate on yielding behaviour, shown in Figure 4, can be described by the Eyring Theory.[10,11] The values of activation energy and stress activation volume are calculated using the Eyring equation for an activated-rate process, which can be written in terms of the strain rate, $\dot{\varepsilon}$, and absolute, T, as

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp[-(E_a - \sigma_y V^*)]/kT \tag{1}$$

where ε_0 is constant, E_a is the activation energy for an activated-rate process, σ_y is the yield stress, V^* is the stress activation volume, k is Boltzmann constant, and T is the absolute temperature. This equation implies that the stress at yield and the logarithm of strain rate have a linear relationship with the slope given by

$$\partial\sigma_y/(\partial \ln \dot{\varepsilon})_T = kT/V^* \tag{2}$$

Values for the activation energy and the activation volume are calculated from the observed linear dependence of Figure 4 for polycarbonate polymer and the prepared composites. Figure 5 shows the variations of activation energy. E_a, and the activation volume, V^*, as a function of weight fraction of PAN carbon fibers. Both of V^* and E_a increases with filler concentration. The activation energy, E_a, increases with the filler content as the yield stress does. This also indicates good interfacial bonding between the fibers and matrix. However the behavior of E_a with the filler concentration is not unique, it differs from composite to another as we have seen in our recent investigations[6,7] and other reported studies.[12,13]

Certainly, there is no straightforward concept or mechanism to predict the E_a behavior as is a function of filler content. To account for this behavior few factors must be taken into consideration. For instance, the yielding phenomenon is strongly dependent on the type of filler as well as on the matrix structure. The reinforcing fibers have influence on the interphase morphology where the transcrystalline region between the fiber and matrix may be quite different from the matrix. Also, the surface fiber history (coated, uncoated, treated) will affect the whole interfacial

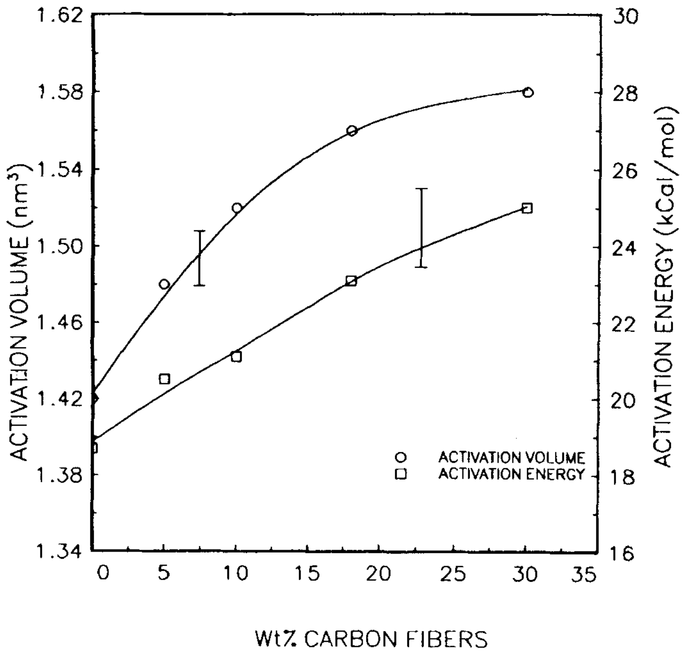

FIGURE 5 Variation of the activation volume and activation energy as a function of PAN-based carbon concentration.

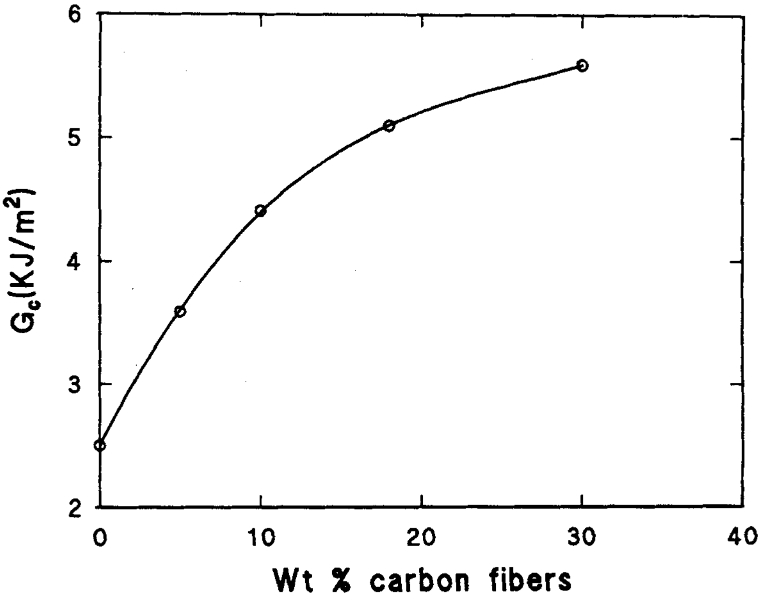

FIGURE 6 The critical strain energy release rate (*Gc*) as a function of carbon fiber content.

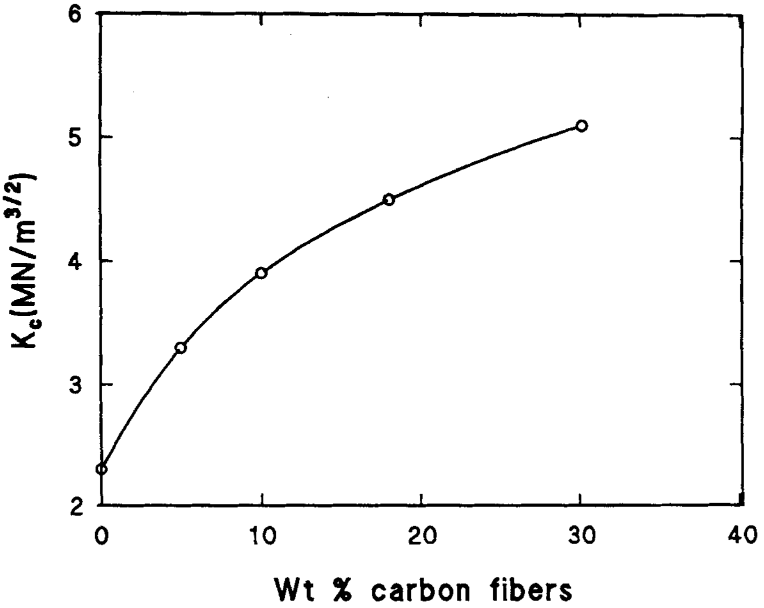

FIGURE 7 The critical stress intensity factor (*Kc*) as a function of carbon fiber content.

mechanism. All these factors certainly will affect, in a peculiar fashion, the E_a behavior as a function of filler content in composites. Finally, it does not appear to have a well defined mechanism that controls the activation energy with increasing the filler content. More decent research work should be devoted to clear the context dealing with the above mentioned structural effects.

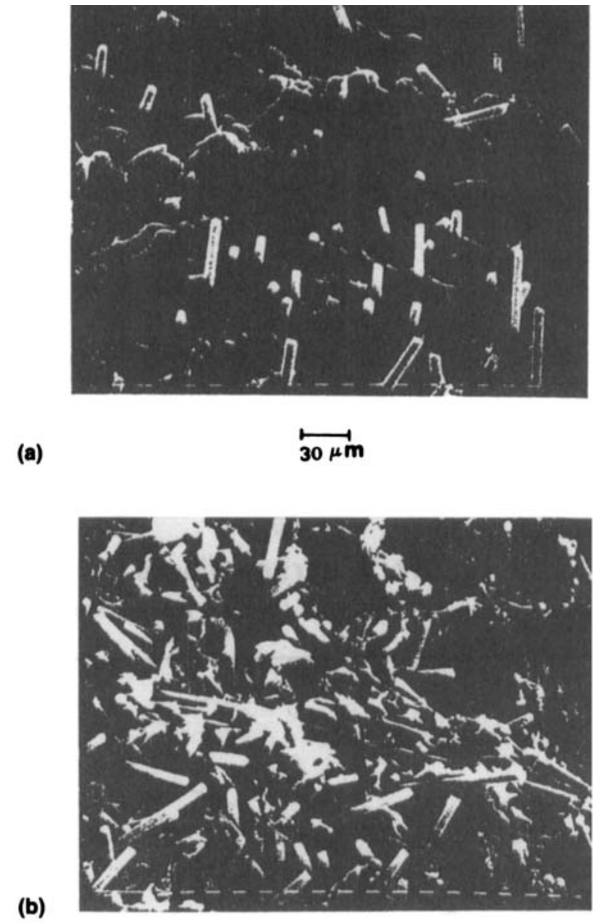

FIGURE 8 Scanning electron micrographs of composites fractured under impact tests. (A) 5 wt% carbon fibers (B) 30 wt% carbon fibers.

3.2 Impact Fracture Results

3.2.1 Fracture toughness parameters. The critical stress intensity factor, K_C is calculated using the fracture mechanics approach[14–16] from the equation

$$K_c = \sigma Y(a)^{1/2} \tag{3}$$

where σ is the nominal stress at the onset of crack propagation, a, is the initial crack length, and Y is a calibration factor depending on the specimen geometry.

For the determination of the critical strain energy release rate, Gc, the following equation is used

$$G_c = U/BW\phi \tag{4}$$

where U is the fracture energy corrected from the kinetic energy contribution, B and W are the thickness and the width of the specimen, respectively, and ϕ is a calibration factor which depends on the lengths of crack and size of the sample. The values were taken from Plati and Williams.[17]

3.2.2 Fracture toughness results. The critical strain energy release rate (*Gc*) as a function of PAN-based carbon content at room temperature is shown in Figure 6. The relationship between *Gc* and fiber content is not a linear one, where the critical strain energy release rate increases with increasing fiber content. The enhancement of *Gc* observed at room temperature is mainly attributed to the occurrence of stiff localized aggregates of carbon fibers and to the existence of entanglement network between the fibers themselves and the polycarbonate matrix. These features of carbon fibers are able to toughen the composites structure.

A similar behavior is observed for the critical stress intensity factor *Kc*.

4. MORPHOLOGICAL STUDY

Optical examination of the molded composites showed relatively smooth surfaces without pores or voids and almost even fiber distribution upon the surfaces. The tensile deformation behaviour of tested composite specimens was characterized by a yielding phenomenon with crazes and shear banding, and finally a failure with relatively straight edge transverse cracks. Figure 8 shows scanning electron micrographs of fractured surfaces of specimens of 5 and 30 wt% PAN-based carbon fibers contents obtained during the fracture tests. Actually, SEM photographs were taken for all fractures composites. It can be seen from the fracture surfaces of low fiber content, 5 and 10 wt% composites, the fibers are in very good adhesion to polycarbonate matrix. The fracture surfaces of the highly fiber content specimens, 18 and 30 wt% show less adhesion due to the large density of carbon fibers and that small number of fibers are not covered by the matrix and pulled out during the fracture process.

This observed morphology can explain the overall behavior of the measured mechanical parameters. The stiffness enhancement is mainly attributed to the carbon fibers of high modulus with respect to the polymer matrix. The increase of the yield stress with increasing of the fiber concentration is due to good interfacial bonding between the fibers and polycarbonate matrix. The matrix deformation is characterized by a ductile and plastic deformation behavior with shear banding as shown from the SEM micrographs. The toughness enhancement with fiber content can be attributed to composite lamination where the applied stress is suddenly accommodated and the impact energy is dispersed through the composite bulk. Thus, during fracture, the amount of energy required to form voids and cracks at the fiber-matrix interface increases with increasing carbon fiber network supporting the applied loads, particularly in the crack-tip zone characterized by a large amount of plastic deformation.[18]

5. CONCLUSION

Polycarbonate based composites reinforced with PAN carbon fibers of high modulus and strength were prepared to study their mechanical properties as a function of fiber content, temperature and strain rate. The following conclusions can be drawn from the results obtained:

1. The stiffness of composites is increased and the yield stress is also increased with increasing the fiber content.
2. The yield stress showed temperature and strain rate dependence.
3. The activation volume and activation energy of yielding process are increased with the carbon fiber concentration.
4. The fracture toughness is enhanced with the fiber content.
5. The observed morphology showed good interfacial bonding and correlates with the measured mechanical parameters.

Acknowledgment

One of the authors (A. Z.) is very grateful to both the International Center for Theoretical Physics at Trieste (Italy), and the University of Jordan (Amman) for financial support. We thank Professor R. J. Farris of U. Mass. in Amherst for providing us the PAN carbon fibers. This work has been partially supported by C.N.R. "Progetto Finalizzato Chimica Fine II." Special thanks to Mr. A. Lahoz for his technical help in composite preparation.

References

1. J. Del Monte, "Metal Polymer Composite," VNR, New York, 1990.
2. G. Lubin, "Handbook of Composites," Von Nostrand, London, 1982.
3. M. A. Meyers and O. T. Inan, "Frontiers in Materials Technologies," Elsevier, Amsterdam, 1985, Chap. 12.
4. R. M. Gill, "Carbon Fibers in Composite Materials," The Plastic Institute, London, 1972.
5. M. Yasin, A. El-Rihail, M. Ahmad and A. Zihlif, *Mat. Chem. Phys.*, **15**, 353 (1986); *Mater. Sci. Eng.*, **86**, 205 (1987).
6. V. Di Liello, E. Martuscelli, G. Ragosta and A. Zihlif, *J. Mater. Sci.*, **26**, 2100 (1991); **25**, 706 (1990).
7. V. Di Liello, E. Martuscelli, G. Ragosta and A. Zihlif, *Intern. J. Polymeric Mater.*, **17**, 93 (1992).
8. M. Ahmad, Y. Ramadin, S. Jawad, A. Zihlif, E. Martuscelli and G. Ragosta, *J. Thermoplas. Compos. Mater.*, **6**, 108 (1993).
9. I. M. Ward, *J. Mater. Sci.*, **6**, 1397 (1971).
10. N. G. Mc Crum, C. Buckley and C. Bucknall, "Principles of Polymer Engineering," Oxford Univ. Press, Oxford, 1989, Chpt. 5.
11. L. Feldman, A. Zihlif, R. Farris and E. Thomas, *J. Mater. Sci.*, **22**, 1199 (1987).
12. S. N. Maito and P. K. Mahapatro, *J. Appl. Polym. Sci.*, **37**, 1989 (1989).
13. S. S. Bhagawan and S. K. De, *Polym. Plast. Technol. Eng.*, **27**, 37 (1983).
14. J. G. Williams, in "Fracture Mechanics of Polymers," Ellis Horwood Limited, New York, 1984, p. 238–292.
15. A. J. Kinloch and R. I. Young, in "Fracture Behaviour of Polymers," Applied Science Publishers, London, 1983.
16. R. Greco and G. Ragosta, *Plast. Rubb. Proc. Appl.*, **7**, 163 (1987).
17. E. Plati and J. Williams, *Polym. Eng. Sci.*, **15**, 470 (1975).