The Effect of Loading Rate on the Fracture Toughness of Fiber Reinforced Polymer Composites

George C. Jacob,[1] J. Michael Starbuck,[2] John F. Fellers,[1] Srdan Simunovic,[3] Raymond G. Boeman[2]

[1]*Materials Science and Engineering Department, University of Tennessee, Knoxville, 434 Dougherty Engineering, Knoxville, TN 37996*
[2]*Polymer Matrix Composites Group, Metals and Ceramics Division, Oak Ridge National Laboratory, Post Office Box 2009, Oak Ridge, TN 37831-8048*
[3]*Computational Material Science, Computer Science and Mathematics Division, Oak Ridge National Laboratory, Post Office Box 2008, Bldg. 6025, MS-6359, Oak Ridge, TN 37831-6359*

Received 23 February 2004; accepted 13 September 2004
DOI 10.1002/app.21535
Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: This article is a detailed review of the strain rate dependence of fracture toughness properties in polymer composite materials. An attempt is made to draw together all the strain rate studies done in the past and to elucidate the reasons given by the authors of the reviewed papers for the trends resulting from their studies to better understand the strain rate effects on the fracture toughness of fiber reinforced polymer composite materials. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 96: 899–904, 2005

Key words: polymer composite materials; strain rate; fracture toughness

INTRODUCTION

Composites in the past have been mainly used for savings in secondary structures. With several advances made in understanding the behavior of composite materials, many fiber reinforced polymer composite materials are finding increasing use as primary load bearing structures and also in a wide range of high technology engineering applications. The ability to tailor composites, in addition to their attributes of high stiffness-to-weight and strength-to-weight ratios, fatigue resistance, corrosion resistance, and lower manufacturing costs, makes them very attractive when compared with conventional metals.

The main drawback of composite systems is their inability to resist defect initiation and propagation when compared to metallic systems. The ability to resist defect propagation is characterized by the fracture toughness of the material. It has always been a cause for concern that the fracture toughness properties of a composite material may be poor at high rates of strain. This calls for investigating the strain rate dependence of fracture toughness properties of composite materials. Indeed, high velocity impact tests on various composites have suggested that beyond a certain threshold velocity, a change in failure mode occurs and the composite material experiences a sudden drop in mechanical performance.

In this article an attempt is made to review much of the work published in the literature that investigates the strain rate effects on the Mode I, Mode II, and Mixed Mode (I+II) fracture toughness properties of fiber reinforced polymer composite materials. Please see Table I for a summary of published data on the effects of loading rate on fracture toughness properties.

LITERATURE SURVEY

Strain rate effects on Mode I fracture toughness of fiber reinforced polymer composites

Aliyu and Daniel[1] used Double Cantilever Beam (DCB) specimens to study the effect of loading rate on fracture toughness of AS-4/3501–6 carbon/epoxy composites. At the lower loading rates, crack extension was monitored visually; while at higher rates, crack extension was monitored by strain gauges mounted on the surface of the specimen or on a conductive paint circuit attached to the edge of the specimen. A 28% increase in the critical strain energy release rate, G_{IC}, was observed over 3 orders of magnitude of loading rate. DCB and Width-Tapered Double Cantilever Beam (WTDCB) interlaminar fracture tests by Daniel et al.[2,3] on a carbon/elastomer modi-

Correspondence to: G. C. Jacob (gjacob@utk.edu).

DISCLAIMER: The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05–00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

Journal of Applied Polymer Science, Vol. 96, 899–904 (2005)

fied epoxy composite at various loading rates resulted in a 20% decrease in G_{IC} over 3 decades of crack velocity, which was attributed to the lower strain to failure of the rubber modified matrix at high strain rates

Using Height-Tapered Double Cantilever Beam (HTDCB) specimen geometry to achieve higher crack velocities, Yaniv and Daniel[4] found that the maximum value of G_{IC} for the AS-4/3501–6 carbon/epoxy composites was around 46% higher than the quasi-static value. In addition to the HTDCB specimen geometry allowing the attainment of much higher crack propagation velocities than was possible with uniform DCB or WTDCB specimens, they also helped produce a stable and smooth crack propagation at high rates of loading. The results obtained by Daniel et al.[1,4] while investigating the AS-4/3501–6 graphite/epoxy composites was attributed to the rate sensitivity (insensitivity or positive or negative rate sensitivity—in this case, positive rate sensitivity) exhibited by the polymer matrix (epoxy) in the composite since Mode I fracture toughness in a composite is a matrix dominated property.

Double Cantilever Beam (DCB) tests by Barbezat[5] on carbon/epoxy composites showed that the Mode I interlaminar fracture toughness does not vary with strain rate. Similar tests by Gillespie, Jr. et al.[6] on carbon/epoxy composites and on a thermoplastic matrix composite, carbon/PEEK, have shown that over a wide range of strain rates the Mode I fracture toughness remains invariant of strain rate. However, beyond a certain threshold, the fracture toughness of the carbon/PEEK composite drops dramatically, to approximately 20% of its original value. This decrease was attributed to a ductile to brittle transition of the polymer in the process zone.

While investigating strain rate effects on fracture toughness of carbon/epoxy and carbon/PEEK composites, Blackman et al.[7] found that fracture toughness of carbon/epoxy composites remained invariant of strain rate (the value being about 0.3 kJ/m^2) and that of the carbon/PEEK composite reduced by 20% at the highest rate. In his work he showed that great care must be taken in the experimental aspects when undertaking high rate tests. To reinforce the comments made on the dynamic effects associated with high rate testing, he noted that the reduction in the fracture toughness value obtained from crack initiation from his work on the carbon/PEEK composite at high strain rate would be far greater had he employed the unreliable and inaccurate values of the measured load at crack initiation to determine the value for G_{IC}.

Kusaka et al.[8] investigated the effect of loading rate on the Mode I fracture toughness of DCB and Wedge-Insert Fracture (WIF) carbon/epoxy composite specimens and found that the value of fracture toughness was constant over a relatively large range of loading rates. The trends resulting from his study were explained using a simple kinetic model.

DCB test geometry was utilized by Smiley and Pipes[9] to investigate the rate effects of Mode I interlaminar fracture toughness in graphite/PEEK and graphite/epoxy composites over a range of crosshead speeds from 4.2×10^{-6} m/s to 6.7×10^{-1} m/s. The Mode I interlaminar fracture toughness of the graphite/PEEK composite decreased from 1.5 to 0.35 kJ/m^2 over 5 decades of opening rate, while that of the graphite/epoxy composite decreased from 0.18 to 0.04 kJ/m^2 over 4 decades of opening rate. The observed rate dependency of the composite fracture toughness was attributed to the rate dependent toughness of the viscoelastic matrix.[10]

The rate dependency of the composite toughness is similar to that of the matrix toughness. Vu-Khanh and Fisa[11] found the dynamic fracture toughness of glass-flake reinforced polypropylene composite is rate dependent. The dynamic fracture toughness first decreases with the increase in impact velocity, reaches a minimum value, and then increases with impact speed. The increase in fracture toughness with loading rate is attributed to the blunting effect of the crack tip, which is induced by a local temperature increase (adiabatic heating).

You and Yum[12] reported a 73% increase in the Mode I interlaminar fracture toughness of brittle carbon/epoxy composite with increasing loading rate from 2 to 120 mm/s. A new technique was proposed from which many crack propagation lengths could be measured in one specimen during high rate testing. However, they did not explain the results they got during their investigation.

Using Compact Tension (CT) specimens, Karger-Kocsis and Friedrich[13] reported a decrease in the fracture toughness of 30 wt % short glass fiber reinforced PEEK composite, with increasing deformation rate down to a level of 1–2 MPa/m^2. The reduction of fracture toughness was explained by a reduced molecular mobility and thus a lower ductility of the polymer matrix (increase in the loading rate caused a total embrittlement of the PEEK matrix between the fibers) at higher loading velocities.

Investigating the effect of loading rate on the Mode I interlaminar fracture toughness of a woven carbon/PEEK laminate by Mall et al.[14,15] highlighted rapid reduction in the fracture toughness with increasing loading rate. The fracture toughness of the DCB specimens decreased up to 65% over 5 decades of loading rate. The extent of plastic deformation decreasing with increasing loading rate was explained to be the reason for the decrease in fracture toughness with increasing loading rate.

The effect of loading rate on the Mode I fracture toughness of epoxy resin composites filled with silica particulates was investigated by Koh et al.[16] Fracture

TABLE I
Summary of Published Data on the Effects of Loading Rate on Fracture Toughness Properties

Authors	Materials studied	Range of rates investigated	Observations
Effect of Loading Rate on Mode I Fracture Toughness Properties			
Daniel et al.[1–4]	Carbon/Epoxy and Carbon/Elastomer Modified Epoxy	0.0075 mm/sec → 460 mm/sec	Fracture toughness increased for carbon/epoxy composites while decreased for carbon/elastomer modified epoxy composites with increasing loading rate.
Barbezat[5]	Carbon/Epoxy	20 mm/min → 3 m/sec	Fracture toughness was rate insensitive.
Gillespie Jr[6]	Carbon/Epoxy and Carbon/PEEK	0.25 mm/min → 250 mm/min	Fracture toughness of carbon/PEEK decreased with increasing loading rate while that of carbon/epoxy was rate insensitive.
Blackman et al.[7]	Carbon/Epoxy and Carbon/PEEK	2 mm/min → 15 m/sec	Fracture toughness of carbon/PEEK decreased with increasing loading rate while that of carbon/epoxy remained invariant of strain rate.
Kusaka et al.[8]	Carbon/Epoxy	0.01 mm/min → 20 m/sec	Fracture toughness was rate independent.
Smiley and Pipes[9]	Carbon/Epoxy and Carbon/PEEK	4.2×10^{-6} m/sec → 6.7×10^{-1} m/sec	Fracture toughness decreased with increasing loading rate.
Vu-Khanh and Fisa[11]	Glass Flake/Polypropylene	0.01 m/sec → 5 m/sec	Fracture toughness decreased with increasing loading rate and after reaching a minimum value then increased with impact speed.
You and Yum[12]	Carbon/Epoxy	0.02 mm/sec → 120 mm/sec	Fracture toughness increased with increasing loading rate.
Karger-Kocis and Friedrich[13]	Short Glass/PEEK	0.1 mm/min → 1000 mm/min	Decrease in fracture toughness with increasing loading rate.
Mall et al.[14,15]	Carbon/PEEK	0.05 cm/min → 100 cm/min	Fracture toughness decreased with increasing loading rate.
Koh et al.[16]	Silica Particulates/Epoxy	5 mm/min → 2.93 m/sec	Increase in fracture toughness with increasing loading rate.
Beguelin et al.[17]	Graphite/PEEK	1×10^{-6} sec^{-1} → 8×10^{-1} sec^{-1}	Fracture toughness decreased with increasing loading rate.
Effect of Loading Rate on Mode II Fracture Toughness Properties			
Smiley and Pipes[18]	Carbon/Epoxy and Carbon/PEEK	4.2×10^{-6} m/sec → 9.2×10^{-2} m/sec	Fracture toughness decreased with increasing loading rate.
Kageyama and Kimpara[19]	Carbon/Epoxy	Static → 8 m/sec	Increase in fracture toughness with increasing loading rate.
Kusaka[20,21]	Carbon/Epoxy	10^{-5} sec^{-1} → 10^{2} sec^{-1}	Fracture toughness decreased with increasing loading rate.
Berger and Cantwell[22,23]	Carbon/Phenolic Resin and Carbon/PEEK	0.1 mm/min → 500 mm/min	Fracture toughness increased for carbon/PEEK composites while decreased for carbon/phenolic resin composites with increasing loading rate.
Cantwell[2425]	Carbon/PEEK	0.01 mm/min → 3 m/sec	Increase in fracture toughness with increasing loading rate.
Maikuma et al.[26]	Carbon/Epoxy and Carbon/PEEK	1.25 m/sec → 3 m/sec	Decrease in fracture toughness with increasing loading rate.
Todo et al.[27]	Carbon/Polyamide	1 mm/min → 1.1 m/sec	Fracture toughness increased with increasing loading rate.
Jar et al.[28,29]	Glass/Epoxy, Glass/Vinylester and Glass/Polyester	1 mm/min → 3 m/sec	Decrease in fracture toughness with increasing loading rate.

TABLE I *Continued*

Authors	Materials studied	Range of rates investigated	Observations
Compston et al.[30]	Glass/Vinylester	1 mm/min → 3 m/sec	Fracture toughness was rate independent.
Chapman et al.[31]	Carbon/Epoxy and Carbon/PEEK	4.2×10^{-6} m/sec → 9.2×10^{-2} m/sec	Fracture toughness decreased with increasing loading rate.
Matsumoto et al.[32]	Glass/Polycarbonate and Glass/Epoxy		Fracture toughness increased with increasing loading rate.
Blackman et al.[33]	Carbon/Epoxy and Carbon/PEEK	1 mm/min → 5 m/sec	Fracture toughness was rate independent.
Effect of Loading Rate on Mixed Mode (I + II) Fracture Toughness Properties			
Blackman et al.[33]	Carbon/Epoxy and Carbon/PEEK	1 mm/min → 5 m/sec	Fracture toughness was found to be rate invariant.
Kusaka et al.[34]	Carbon/Epoxy	10^{-6} m/sec → 10 m/sec	Fracture toughness decreased with increasing loading rate.
Cantwell et al.[35]	Carbon/PEEK	0.05 mm/min → 3 m/sec	Increase in fracture toughness with increasing loading rate.
Blyton[36]	Carbon/Epoxy and Glass/Polypropylene		Fracture toughness was rate independent.

toughness under static loading was found to be slightly lower than that of impact loading. The loading rate dependence was related to the dynamic effects of the impact tests and the particle-matrix debonding near the initial crack tip. Slow loading rates promoted interfacial debonding of otherwise well bonded particles, which caused a reduction in the resistance of the material to gross failure. The debonding deteriorated the full capability of the matrix material for shear deformation due to premature failure. The dynamic effects included the relatively high contact stiffness of the impact striker-specimen interface compared to that of the specimen, and the loss and regaining of contact between the striker and the specimen accelerating and decreasing relative to the striker during impact loading. All the effects resulted in an increasing number of oscillations observed in the force–displacement curve of the impact test as the impact velocity was increased.

DCB tests by Beguelin et al.[17] on unidirectional IM6 graphite/PEEK composites showed a small decrease in the Mode I interlaminar fracture toughness at very high strain rates. At higher rates the analysis was performed by means of Fast Fourier Transform (FFT) filtering.

Strain rate effects on Mode II fracture toughness of fiber reinforced polymer composites

End Notch Flexure (ENF) specimen geometries were used by Smiley and Pipes[18] to investigate the loading rate effects on the Mode II interlaminar fracture toughness of carbon/epoxy (AS4/3501–6) and carbon/PEEK (APC-2) composites. The fracture toughness of both carbon/epoxy and carbon/PEEK composites decreased by about 85% at high loading rates. The reduction in the fracture toughness of the thermoplastic carbon/PEEK composite was attributed to a decrease in the development of plastic deformation during loading.

Kageyama and Kimpara[19] investigated the effect of loading rate on the Mode II interlaminar fracture toughness of a unidirectional carbon/epoxy laminate. The fracture toughness was found to increase with increasing impact velocity, and the value at the impact velocity of 8 m/s was 1.8 times higher than the static value. No explanation was give for the observed results.

Kusaka et al.[20,21] explored the strain rate effects of fracture toughness of unidirectional carbon/epoxy composites using a split Hopkinson pressure bar (SHPB) and found that the fracture toughness decreased by 20% over 8 decades of loading rate. The SEM observations indicated that the results were caused by fractographic differences: The specimen fracture surfaces were smooth at high strain rates as a result of debonding at the fiber matrix interface, and the matrix surface is only deformed a little; but the specimen fracture surfaces at low rates highlighted the presence of hackle markings due to ductile fracture in the matrix resin. The dynamic strength of bonding between reinforcing fibers and matrix resin might have been lower than the static strength.

Berger and Cantwell found that the Mode II interlaminar fracture toughness of carbon fiber reinforced phenolic resin decreased with increasing load rate,[22] while that of carbon fiber reinforced PEEK increased with increasing loading rate.[23] SEM observations of a number of samples indicated the interlaminar fracture toughness of the carbon/phenolic resin composite was determined by the development of the damage zone in the crack tip region. It was suggested that the Mode II interlaminar fracture energy was directly dependent on the amount of plastic deformation in front of the crack tip.[22] The Mode II interlaminar fracture toughness of the carbon/PEEK composite was believed to be strongly influenced by the yield stress of the thermoplastic matrix. Conditions that reduce the yield stress of the polymer (such as decreasing the loading rate) precipitate similar reductions in the value of Mode II fracture toughness.[23]

Cantwell,[24,25] while investigating the effect of loading rate in the fracture toughness of a carbon/PEEK composite material, found that the Mode II interlaminar fracture toughness of the composite increased with increasing loading rate. The viscoelastic response exhibited by the matrix of the fiber reinforced plastic and the interphase was suggested to influence the fracture toughness properties.

Maikuma et al.[26] investigated the effect of loading rate on the fracture toughness of Center Notch Flexure (CNF) specimen geometries of carbon/PEEK and carbon/epoxy composites. The initiation value of fracture toughness was determined using a beam theory analysis, and it was observed that the impact initiation toughness of carbon/PEEK and carbon/epoxy composites were approximately 20 and 28% lower than their corresponding static values. This decrease was attributed to less ductile tearing and plastic deformation at higher loading rates.

Todo et al.[27] reported a 53% increase in the Mode II interlaminar fracture toughness of a carbon fiber reinforced polyamide as the loading rate was increased from 1 mm/min to 1.1 m/s and attributed this effect to the positive rate sensitivity of the thermoplastic matrix.

Jar et al.[28,29] used the CNF geometry to study the loading rate effects on the interlaminar fracture toughness of glass/epoxy, glass/vinylester, and glass/polyester composites and found that the dynamic values of interlaminar fracture toughness were about 60% of the static values. No explanations were given for the results.

Compston et al.[30] investigated the effect of loading rate on the Mode II interlaminar fracture toughness of unidirectional glass fiber composites with brittle and rubber toughened vinyl ester matrices by conducting Mode II tests on ENF specimens at test rates ranging from 1 mm/min to 3 m/s. There was no significant effect of loading rate on fracture toughness for the glass/vinyl ester composite. Fracture surface micrographs for the composite at different rates showed no significant difference in matrix deformation between rates, and the clean fiber surfaces indicated significant interfacial failure at various rates. These observations supported the conclusion of no rate effect.

Chapman et al.,[31] while investigating the effect of loading rate on Mode II interlaminar fracture toughness of ENF specimen geometries of carbon/PEEK and carbon/epoxy composites, found a reduction in the fracture toughness of both composites at high rates. The drop in toughness was attributed to a decrease in plastic deformation and change from ductile to brittle behavior as rate was increased.

Matsumoto et al.[32] used the Curvature Driven Delamination (CDD) test to study the effect of loading rate on the Mode II interlaminar fracture toughness of glass/polycarbonate and glass/epoxy composites. The fracture toughness of the glass/polycarbonate composite increased by approximately 22% over 3 decades of loading rate and so did that of the glass/epoxy composite. However, no explanations for the above trend were given.

While investigating strain rate effects on Mode II fracture toughness of carbon/epoxy and carbon/PEEK composites using End Loaded Split test (ELS) geometry, Blackman et al.[33] found that fracture toughness of both the composites remained invariant of strain rate. In this investigation, similar to his previous work,[7] he showed that great care must be taken in the experimental aspects when undertaking high rate tests.

Strain rate effects on Mixed Mode (I+II) fracture toughness of fiber reinforced polymer composites

Kusaka et al.[34] used the Mixed Mode Flexure (MMF) specimen and Split Hopkinson Pressure Bar (SHPB) system to measure the mixed mode (I+II) fracture toughness of an interlayer toughened carbon fiber/epoxy composite system over a wide range of loading rates. The experimental results showed that the mixed mode fracture toughness was loading rate sensitive; the impact fracture toughness was about 30–38% lower than the static value. The microscopic fracture morphology was rather sensitive to loading rate: The impact fracture surface was smoother than the static fracture surface.

Cantwell et al.[35] used MMF specimens to investigate the effect of loading rate on the Mixed Mode (I+II) fracture toughness of carbon/PEEK composites. Tests were conducted over 6 decades of loading rate, and it was found that the mixed mode fracture toughness tended to increase slightly with loading rate. The increase in fracture toughness with loading rate was attributed to the increased localized damage that occurred at high rates of loading.

Blyton[36] investigated loading rate effects on the Mixed Mode (I+II) fracture toughness of carbon/epoxy, glass/polypropylene, and woven carbon/toughened epoxy composites and found all of the composites to be rate insensitive.

Blackman et al.[33] used the Fixed Ratio Mixed Mode (FRMM) test to investigate the effect of strain rate on the Mixed Mode (I+II) fracture toughness of carbon/epoxy and carbon/PEEK composites. The Mixed Mode (I+II) fracture toughness of both the composites was found to be strain rate invariant.

CONCLUSIONS

In this article an attempt was made to review all the work done in the past to investigate the strain rate effects on the Mode I, Mode II, and Mixed Mode (I+II) fracture toughness properties of fiber reinforced polymer composite materials. An effort was made to elucidate the reasons given by the authors of the reviewed papers for the trends observed in their work. Upon reviewing the literature, there seems to be a lack of consensus about the influence of loading rate on the fracture toughness properties in composite materials. Hence, more work needs to be done in the pursuit of eliminating all the disagreements that currently exist regarding the effect of loading rate on fracture toughness properties. In some studies no attempt was made to explain the trends resulting from the investigation. Some of the researchers whose works have been reviewed in this manuscript have shown that great care must be taken in the experimental aspects when conducting high rate tests. Lack of sensitivity towards dynamic effects by many researchers might be the cause of the lack of consensus on the effects of high rates on fracture toughness properties.

A couple of general statements can be made that suit most test results: Changes in loading rate can affect the properties of the polymer matrix, which can in turn decide the effects of loading rate on the fracture toughness of the composite. So, basically, the rate sensitivity of the polymer matrix properties determines the rate sensitivities of the polymer composite. Also, changes in loading rate can affect the failure mode in the composite, which can in turn decide the loading rate effects on the fracture toughness properties. Transition from a ductile to a brittle failure mode with increasing loading rates is accompanied by a reduction in the fracture toughness of the composite with increasing loading rates.

It must also be noted that there is no literature available on the effect of strain rate on fracture toughness properties of random chopped fiber reinforced composite materials that can find extensive use in a wide range of load-bearing engineering and industrial process applications primarily due to the low costs involved in their manufacture in addition to the ease of manufacture. Hence, one suggests the need for investigating and characterizing the strain rate effects on fracture toughness of random chopped fiber composites.

Research was sponsored in part by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, Lightweight Materials Program, under contract DE-AC05–00OR22725 with UT-Battelle, LLC. The support of Automotive Composites Consortium Energy Management Group is acknowledged.

References

1. Aliyu, A. A.; Daniel, I. M. In Delamination and Debonding of Materials; Johnson, W. S., Ed.; ASTM STP876, American Society for Testing and Materials: Philadelphia, 1985; p 336.
2. Daniel, I. M.; Shareef, I.; Aliyu, A. A. In Toughened Composites; Johnston, N. J., Ed.; ASTM STP937, American Society for Testing and Materials: Philadelphia, 1987; p 260.
3. Daniel, I. M.; Yaniv, G.; Auser, J. W. In Proc 4th Int Conf on Composite Structures; Marshall, I. H., Ed.; Elsevier, 1987; p 2.258.
4. Yaniv, G.; Daniel, I. M. In Composite Materials Testing and Design 8th Conference; Whitcomb, J. D., Ed.; ASTM STP972, American Society for Testing and Materials: Philadelphia, 1988; p 241.
5. Barbezat, M. Ph.D. Thesis, Ecole Polytechnique Federale de Lausanne, Switzerland, 1990.
6. Gillespie, Jr, J. W.; Carlsson, L. A.; Smiley, A. J. Comp Sci & Tech 1987, 28, 1.
7. Blackman, B. R. K.; Dear, J. P.; Kinloch, A. J.; MacGillivray, H.; Wang, Y.; Williams, J. G.; Yayla, Y. J Mat Sci 1995, 30, 5885.
8. Kusaka, T.; Hojo, M.; Mai, Y. W.; Kurokawa, T.; Ochiai, S. Comp Sci Tech 1998, 58, 591.
9. Smiley, A. J.; Pipes, R. B. J of Composite Materials 1987, 21, 670.
10. Friedrich, K.; Walter, R.; Carlsson, L. A.; Smiley, A. J.; Gillespie, Jr, J. W. J Materials Science 1989, 24, 3387.
11. Vu-Khanh, T.; Fisa, B. Polymer Composites 1986, 7, 375.
12. You, H.; Yum, Y. J. J Reinforced Plastics Composites 1997, 16, 537.
13. Karger-Kocsis, J.; Friedrich, K. Polymer 1986, 27, 1753.
14. Mall, S.; Law, G. E.; Katouzian, M. Proc SEM Spring Conf on Experimental Mechanics 1986, 412.
15. Mall, S.; Law, G. E.; Katouzian, M. J of Composite Materials 1987, 21, 569.
16. Koh, S.-W.; Kim, J.-K.; Mai, Y.-W. Polymer 1993, 34, 3446.
17. Beguelin, P.; Barbezat, M.; Kausch, H. H. J de Physique III 1991, 1, 1867.
18. Smiley, A. J.; Pipes, R. B. Comp Sci Tech 1987, 29, 1.
19. Kageyama, K.; Kimpara, I. Materials Science and Engineering 1991, A143, 167.
20. Kusaka, T.; Yamauchi, Y.; Kurokawa, T. J De Physique IV 1994, 4, C8–671.
21. Kusaka, T.; Kurokawa, T.; Hojo, M.; Ochiai, S. Key Eng Mats 1998, 141–143, 477.
22. Berger, L.; Cantwell, J. Polymer Composites 2001, 22, 165.
23. Berger, L.; Cantwell, J. Polymer Composites 2001, 22, 271.
24. Cantwell, W. J. J Mats Sci Lett 1996, 15, 639.
25. Cantwell, W. J. J of Composite Materials 1997, 31, 1364.
26. Maikuma, H.; Gillespie, J. W.; Wilkins, D. J. J of Composite Materials 1990, 24, 124.
27. Todo, M.; Nakamura, T.; Takahashi, K. J Reinforced Plastics and Comp 1999, 18, 1415.
28. Jar, P. Y. B.; Compston, P.; Davies, P.; Takahashi, K. In Proc of 6th Int Conf in Marine Applications of Composite Mats, The Association: Cocoa Beach, FL, 1996; Vol. 6, pp 1–12.
29. Compston, P.; Jar, P.-Y. B.; Davies, P. Composites Part B 1998, 29, 505.
30. Compston, P.; Jar, P.-Y. B.; Burchill, P. J.; Takahashi, K. Comp Sci and Tech 2001, 61, 321.
31. Chapman, T. J.; Smiley, A. J.; Pipes, R. B. In Proc. ICCM6/ECCM2; Matthews, F. L.; Buskell, N. C. R.; Hodgkinson, J.; Morton, J. Eds.; Elsevier: New York, 1987; p 3.295.
32. Matsumoto, D. S.; McKinley, B. J.; Todt, M. L.; Giffords, S. K. General Electric Res. Report No. 89CRD104.
33. Blackman, B. R. K.; Dear, J. P.; Kinloch, A. J.; MacGillivray, H.; Wang, Y.; Williams, J. G.; Yayla, Y. J Mat Sci 1996, 31, 4467.
34. Kusaka, T.; Horikawa, N.; Masuda, M. J De Physique IV 2000, 10, 317.
35. Cantwell, W. J.; Blyton, M.; Sixsmith, P.; Hiley, M. J Mats Sci Lett 1998, 17, 1103.
36. Blyton, M. Ph.D. Thesis, University of Liverpool, UK, 1999.