Fracture Toughness in Random-Chopped Fiber-Reinforced Composites and their Strain Rate Dependence

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ABSTRACT: While many scientists have investigated the fracture toughness properties in various continuous fiber-reinforced composite materials and their dependence on strain rate, there is absolutely no literature available on the fracture toughness properties of random-chopped fiber-reinforced composite materials and their strain rate dependence, which 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. Therefore, the primary goal of this manuscript is to determine the fracture toughness of various random-chopped carbon fiber composite material systems. The four different random-chopped carbon-reinforced epoxy composite material systems studied were P4, HexMC, CCS150, and CCS100. In addition, an attempt is made to investigate and characterize the strain rate effects on the fracture toughness of a random-chopped carbon fiber P4 composite. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 100: 695–701, 2006

Key words: composites; mechanical properties; fibers; resins

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. Of late there has been a trend towards lean weight vehicle structures that has paved the way for increased utilization of polymer composite materials in the automobile industry.

The main draw back of composite systems is their inability to resist defect initiation and propagation when compared with metallic systems. Investigation in the past has shown that even low-energy impacts are capable of generating enough damage to cause significant reductions in their load-bearing capacity.[1–4] The ability to resist defect propagation is characterized by the fracture toughness of the material. While many scientists have investigated the fracture toughness properties in various continuous fiber-reinforced composite materials there is no literature available on the fracture toughness properties of random-chopped fiber-reinforced composite materials, which 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. Therefore, in this study, an attempt is made to determine the fracture toughness of various random-chopped carbon fiber composite material systems. In fact, not much has been said in the literature about the performance properties of any chopped fiber polymer composite systems. On the whole, random-chopped fiber composites are still regarded as relatively new materials in the field and often lack the detailed material property and performance characterization that are required before they can be used extensively in various applications. Interested readers can refer to our work on automotive crashworthiness wherein we have looked at the specific energy absorption in a compression-molded random-chopped carbon fiber

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TABLE I
Summary of Published Data on the Effects of Loading Rate on Fracture Toughness Properties of Continuous Fiber-Reinforced Composites

Authors	Materials studied	Range of rates investigated	Observations
Effect of loading rate on mode I fracture toughness properties			
Daniel and coworkers [10–13]	Carbon/epoxy and carbon/elastomer-modified epoxy	0.0075 mm/s to 460 mm/s	Fracture toughness increased for carbon/epoxy composites while decreased for carbon/elastomer-modified epoxy composites, with increasing loading rate
Barbezat [14]	Carbon/epoxy	20 mm/min to 3 m/s	Fracture toughness was rate insensitive
Gillespie Jr. et al. [15]	Carbon/epoxy and carbon/PEEK	0.25 mm/min to 250 mm/min	Fracture toughness of carbon/PEEK decreased with increasing loading rate while that of carbon/epoxy was rate insensitive
Blackman et al. [16]	Carbon/epoxy and carbon/PEEK	2 mm/min to 15 m/s	Fracture toughness of carbon/PEEK decreased with increasing loading rate while that of carbon/epoxy remained invariant of strain rate
Kusaka et al. [17]	Carbon/epoxy	0.01 mm/min to 20 m/s	Fracture toughness was rate independent
Smiley and Pipes [18]	Carbon/epoxy and carbon/PEEK	4.2×10^{-6} m/s to 6.7×10 [−1 m/s	Fracture toughness decreased with increasing loading rate
Vu-Khanh and Fisa [19]	Glass flake/polypropylene	0.01 m/s to 5 m/s	Fracture toughness decreased with increasing loading rate, and after reaching a minimum value, increased with impact speed
You and Yum [20]	Carbon/epoxy	0.02 mm/s to 120 mm/s	Fracture toughness increased with increasing loading rate
Karger-Kocis and Friedrich [21]	Short glass/PEEK	0.1 mm/min to 1000 mm/min	Decrease in fracture toughness with increasing loading rate
Mall et al. [22,23]	Carbon/PEEK	0.05 cm/min to 100 cm/min	Fracture toughness decreased with increasing loading rate
Koh et al. [24]	Silica particulates/epoxy	5 mm/min to 2.93 m/s	Increase in fracture toughness with increasing loading rate
Beguelin et al. [25]	Graphite/PEEK	1 × 10 [−6 s [−1 to 8 × 10 [−1 s [−1	Fracture toughness decreased with increasing loading rate
Effect of loading rate on mode II fracture toughness properties			
Smiley and Pipes [26]	Carbon/epoxy and carbon/PEEK	4.2 × 10 [−6 m/s to 9.2 × 10 [−2 m/s	Fracture toughness decreased with increasing loading rate
Kageyama and Kimpara [27]	Carbon/epoxy	Static to 8 m/s	Increase in fracture toughness with increasing loading rate
Kusaka et al. [28,29]	Carbon/epoxy	10 [−5 s [−1 to 10 [2 s [−1	Fracture toughness decreased with increasing loading rate
Berger and Cantwell [30,31]	Carbon/phenolic resin and carbon/PEEK	0.1 mm/min to 500 mm/min	Fracture toughness increased for carbon/PEEK composites while decreased for carbon/phenolic resin composites, with increasing loading rate
Cantwell [32,33]	Carbon/PEEK	0.01 mm/min to 3 m/s	Increase in fracture toughness with increasing loading rate
Maikuma et al. [34]	Carbon/epoxy and carbon/PEEK	1.25 m/s to 3 m/s	Decrease in fracture toughness with increasing loading rate
Todo et al. [35]	Carbon/polyamide	1 mm/min to 1.1 m/s	Fracture toughness increased with increasing loading rate
Jar and coworkers [36,37]	Glass/epoxy, glass/vinylester, and glass/polyester	1 mm/min to 3 m/s	Decrease in fracture toughness with increasing loading rate
Compston et al. [38]	Glass/vinylester	1 mm/min to 3 m/s	Fracture toughness was rate independent
Chapman et al. [39]	Carbon/epoxy and carbon/PEEK	4.2×10^{-6} m/s to 9.2×10^{-2} m/s	Fracture toughness decreased with increasing loading rate
Matsumoto et al. [40]	Glass/polycarbonate and glass/epoxy		Fracture toughness increased with increasing loading rate

TABLE I. (Continued)

Authors	Materials studied	Range of rates investigated	Observations
Blackman et al. [41]	Carbon/epoxy and carbon/PEEK	1 mm/min to 5 m/s	Fracture toughness was rate independent
Effect of loading rate on mixed mode (I + II) fracture toughness properties			
Blackman et al. [41]	Carbon/epoxy and carbon/PEEK	1 mm/min to 5 m/s	Fracture toughness was found to be rate invariant
Kusaka et al. [42]	Carbon/epoxy	10^{-6} m/s to 10 m/s	Fracture toughness decreased with increasing loading rate
Cantwell et al. [43]	Carbon/PEEK	0.05 mm/min to 3 m/s	Increase in fracture toughness with increasing loading rate
Blyton [44]	Carbon/epoxy and glass/polypropylene		Fracture toughness was rate independent

epoxy system and compared its performance with other composite systems.[5–9]

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.

Many scientists have investigated the effect of loading rate on the fracture toughness properties in various continuous fiber-reinforced composite materials. See Table I for a summary of the published data on the effects of loading rate on the mode I, mode II, and mixed mode (I + II) fracture toughness properties of various continuous fiber-reinforced composite materials. But again, there is no literature available on the effect of loading rate on the fracture toughness properties of random-chopped fiber-reinforced composite materials. Therefore, in this study, an attempt is made to also investigate the strain rate dependence of a random-chopped carbon fiber P4 composite.

EXPERIMENTAL

The CCS100 and CCS150 composite plates were manufactured from Toray T700 chopped carbon fiber with YLA RS-35 epoxy resin, using compression molding techniques. While YLA supplied the molding compound; CCS Composites LLC compression molded the plates. The CCS100 (100 gsm tow size) and CCS150 (150 gsm tow size) composites had a fiber volume fraction of 50% and a fiber length of 1 in. The random-chopped carbon fiber epoxy resin HexMC composite plates, which had a fiber volume fraction of 57% and 2 in. fiber length, were compression molded by Hexcel Composites LLC. The compression molded P4 composite plates were manufactured from chopped carbon fiber having 2 in. length and 36% fiber volume fraction with Hetron epoxy resin. The above four random-chopped carbon-reinforced epoxy composite material systems were tested using a Servo hydraulic test machine at a loading rate of 0.15 cm/min (0.06 in./min). However, the P4 composite material system was tested at additional rates of 15.2 cm/min (6 in./min), and 762 cm/min (300 in./min) to investigate their strain rate dependence. Fracture toughness tests were run as per ASTM D5045–99 (SENB method) and the load–deflection response was recorded using a computerized data acquisition system.

RESULTS AND DISCUSSION

On comparing the performance of the P4, HexMC, CCS150, and CCS100 composite plates, the fracture toughness of the HexMC composite was found to be the highest followed by CCS150, CCS100, and P4 in the order of decreasing fracture toughness. For a comparison of the fracture toughness of P4, HexMC, CCS150, and CCS100 composites see Tables II–V.

The HexMC composites had a fiber volume fraction of 57% followed by the CCS150 and CCS100 composites (50%) and the P4 composite had the lowest fiber volume fraction (36%). This indicates the effect of fiber volume fraction on the fracture toughness properties of chopped carbon fiber composites, with increased fiber volume fracture leading to higher fracture toughness properties. The above is in agreement with what one would normally think that an increase in the fiber content would improve the performance properties of a composite.

The fact that the CCS150 composite having a tow size of 150 gsm recorded a higher fracture toughness value than the CCS100 composite having a tow size of 100 gsm indicates a positive influence of an increased tow size on the fracture toughness properties of chopped carbon composites. The HexMC composites that displayed superior fracture toughness properties had a fiber length of 2 in. while the P4 composite which recorded the least fracture toughness values also had a fiber length of 2 in. Hence, not much can be

TABLE II
Fracture Toughness Data from Tests Conducted at 0.15 cm/min Loading Rate on HexMC

Specimen ID	Avg. width, W (mm)	Avg. thickness, b (mm)	a/W	$f(a/W)$	K_{IC} (MPa m$^{1/2}$)
HEXMC1	12.695	3.117	0.50	10.65	7.12
HEXMC2	12.690	3.100	0.50	10.65	7.03
HEXMC3	12.700	3.070	0.50	10.65	6.61
HEXMC4	12.675	3.133	0.50	10.65	6.07
HEXMC5	12.695	3.077	0.50	10.65	6.46
HEXMC6	12.705	3.130	0.50	10.65	6.26
HEXMC7	12.700	3.087	0.50	10.65	6.84
HEXMC8	12.705	3.117	0.50	10.65	6.70
HEXMC9	12.690	3.110	0.50	10.65	6.54
HEXMC10	12.690	3.123	0.50	10.65	6.82
Average					6.64

read into effect of fiber length on fracture toughness properties of chopped carbon fiber composites from the above results.

Since the HexMC and the P4 composite material systems recorded the highest and lowest fracture toughness properties, respectively, an attempt was made to also determine the flexural properties of these two random-chopped carbon fiber composite materials systems to see how they compared and verify whether the same trend persisted. Four-point flexure tests were run as per ASTM D6272–00 and the load–deflection response was recorded using a computerized data acquisition system. The composite specimen plate was made to rest on two supports

TABLE III
Fracture Toughness Data from Tests Conducted at 0.15 cm/min Loading Rate on CCS150

Specimen ID	Avg. width, W (mm)	Avg. thickness, b (mm)	a/W	$f(a/W)$	K_{IC} (MPa m$^{1/2}$)
CFF1508	12.695	3.140	0.50	10.65	3.55
CCF1509	12.695	3.170	0.50	10.65	6.20
CCF15010	12.705	3.153	0.50	10.65	10.23
CCF15011	12.695	3.130	0.50	10.65	8.56
CCF15012	12.685	3.127	0.50	10.65	7.28
CCF15013	12.700	3.143	0.50	10.65	7.16
CCF15014	12.705	3.160	0.50	10.65	6.98
CCF15015	12.700	3.153	0.50	10.65	3.10
CCF15016	12.695	3.147	0.50	10.65	1.14
CCF15017	12.700	3.150	0.50	10.65	8.64
CCF15018	12.690	3.147	0.50	10.65	2.93
CCF15019	12.695	3.143	0.50	10.65	9.34
Average					6.26

TABLE IV
Fracture Toughness Data from Tests Conducted at 0.15 cm/min Loading Rate on CCS100

Specimen ID	Avg. width, W (mm)	Avg. thickness, b (mm)	a/W	$f(a/W)$	K_{IC} (MPa m$^{1/2}$)
SENBA1	12.700	3.010	0.50	10.65	4.89
SENBA2	12.680	2.923	0.50	10.65	5.41
SENBA3	12.700	3.240	0.50	10.65	7.64
SENBA4	12.690	3.057	0.50	10.65	5.63
SENBA5	12.675	3.150	0.50	10.65	4.40
SENBF1	12.680	2.940	0.50	10.65	6.15
SENBF2	12.700	2.930	0.50	10.65	6.44
SENBF3	12.700	2.957	0.50	10.65	5.46
SENBF4	12.700	2.943	0.50	10.65	5.12
SENBF5	12.700	2.903	0.50	10.65	6.72
Average					5.79

TABLE V
Fracture Toughness Data from Tests Conducted at 0.15 cm/min Loading Rate on P4

Specimen ID	Avg. width, W (mm)	Avg. thickness, b (mm)	a/W	$f(a/W)$	K_{IC} (MPa $m^{1/2}$)
FRACTTOUGH0_06P41	12.700	3.587	0.50	10.65	3.38
FRACTTOUGH0_06P42	12.700	3.533	0.50	10.65	4.56
FRACTTOUGH0_06P43	12.700	3.497	0.50	10.65	2.23
FRACTTOUGH0_06P44	12.695	3.490	0.50	10.66	2.87
FRACTTOUGH0_06P45	12.695	3.510	0.50	10.66	2.31
FRACTTOUGH0_06P46	12.695	3.473	0.50	10.66	3.68
FRACTTOUGH0_06P47	12.690	3.460	0.50	10.66	3.50
FRACTTOUGH0_06P48	12.700	3.423	0.50	10.65	3.73
FRACTTOUGH0_06P49	12.695	3.417	0.50	10.66	2.77
FRACTTOUGH0_06P410	12.685	3.420	0.50	10.67	2.93
Average					3.19

and was loaded at two points by means of two loading noses, each at an equal distance from the adjacent support point. The alignment of the support and loading anvils were properly ensured. Flexure testing produces tensile stress in the convex side of the specimen and compression stress in the concave side. This creates an area of shear stress along the midline. To ensure that primary failure comes from the tensile or compression stress, the shear stress must be minimized. This was done by using a support span-to-depth ratio of 16:1 (ASTM D6272–00). The specimen was loaded until rupture occurred in the fibers. For a comparison of the flexure properties of P4 and HexMC composites see Tables VI and VII. The maximum strain recorded for both the automotive composites were quite similar, but the maximum stress recorded by the HexMC composite was much greater than that recorded by the P4 composite. This resulted in the HexMC composites recording much higher stiffness than the P4 composites. The superior flexural performance of the HexMC composite is in agreement with the fracture toughness property results also reported in this manuscript. The above is also in agreement with some flexure studies conducted by us in the past[7] on a different chopped carbon fiber composite system wherein also it was concluded that the higher fiber volume fraction tests resulted in higher

TABLE VI
P4 4-Point Flexural Properties

Specimen no.	Specimen width, W (mm)	Specimen thickness, d (mm)	Support span, S (mm)	S/d	Max. stress (MPa)	Max. strain (%)	Stiffness (MPa)
FLEX0_06P41	12.70	3.23	50.80	16	48.58	1.164	5963.75
FLEX0_06P42	12.70	3.18	50.80	16	52.67	1.565	5573.59
FLEX0_06P43	12.70	3.19	50.80	16	44.24	0.925	5809.90
FLEX0_06P44	12.71	3.24	50.80	16	53.32	1.313	6696.97
FLEX0_06P45	12.70	3.20	50.80	16	52.04	1.026	8123.84
FLEX0_06P46	12.70	3.14	50.80	16	54.66	1.196	6010.74
FLEX0_06P47	12.70	3.16	50.80	16	44.38	1.229	5526.04
FLEX0_06P48	12.70	3.16	50.80	16	67.98	1.240	6855.54
FLEX0_06P49	12.70	3.22	50.80	16	62.35	1.637	5497.06
FLEX0_06P410	12.69	3.18	50.80	16	53.56	1.028	6347.46
FLEX0_06P411	12.74	3.23	50.80	16	48.29	1.371	5465.88
FLEX0_06P412	12.57	3.33	50.80	16	58.83	1.157	7016.07
FLEX0_06P413	12.72	3.21	50.80	16	50.22	0.920	6646.47
FLEX0_06P414	12.73	3.23	50.80	16	50.24	1.002	6710.25
FLEX0_06P415	12.72	3.24	50.80	16	51.78	1.431	6153.86
FLEX0_06P416	12.72	3.24	50.80	16	60.55	1.084	8517.53
FLEX0_06P417	12.73	3.26	50.80	16	49.59	1.187	6325.21
FLEX0_06P418	12.72	3.24	50.80	16	67.22	1.465	7619.67
FLEX0_06P419	12.73	3.24	50.80	16	68.05	1.394	8345.85
FLEX0_06P420	12.73	3.28	50.80	16	49.24	1.459	5558.08
FLEX0_06P421	12.73	3.21	50.80	16	78.14	1.827	7569.35
Average value					55.52	1.268	6587.29

TABLE VII
HexMC 4-Point Flexural Properties

Specimen no.	Specimen width, W (mm)	Specimen thickness, d (mm)	Support span, S (mm)	S/d	Max. stress (MPa)	Max. strain (%)	Stiffness (MPa)
FLEXHEXMC1	12.71	3.13	50.80	16	427.56	0.965	44766.06
FLEXHEXMC2	12.70	3.14	50.80	16	595.90	1.072	55299.51
FLEXHEXMC3	12.70	3.13	50.80	16	608.00	1.435	52029.82
FLEXHEXMC4	12.71	3.18	50.80	16	519.20	1.299	45431.76
FLEXHEXMC5	12.71	3.21	50.80	16	445.28	1.086	42478.71
FLEXHEXMC6	12.71	3.21	50.80	16	534.50	1.262	46146.80
Average value					521.74	1.187	47692.11

flexural strengths and stiffnesses. An increase in the fiber content improves the performance properties of a composite.

On loading the P4 composite plate specimens at 0.15, 15.2, and 762 cm/min, respectively, the fracture toughness properties of the P4 composite was found to increase with loading rate. For a comparison of the fracture toughness of P4 composites at loading rates of 0.15, 15.2, and 762 cm/min please see Tables V, VIII, and IX. The increase in fracture toughness with increase in loading rate from 0.15 to 762 cm/min is because of the brittle nature of the P4 composite. For brittle fiber resin composites, an increase in loading rate causes an increase in the fracture toughness of the composite due to the increased fracture toughness of the epoxy matrix resin in the composite with increasing loading rate.

Hence, we see that the strain rate effect on the fracture toughness properties of the P4 chopped carbon fiber composite is similar to that of other brittle continuous fiber-reinforced composites wherein an increase in loading rate causes an in-

TABLE VIII
Fracture Toughness Data from Tests Conducted at 15.2 cm/min Loading Rate on P4

Specimen ID	Avg. width, W (mm)	Avg. thickness, b (mm)	a/W	$f(a/W)$	K_{IC} (MPa $m^{1/2}$)
FRACTTOUGH6P411	12.700	3.400	0.50	10.65	5.88
FRACTTOUGH6P412	12.695	3.387	0.50	10.66	6.72
FRACTTOUGH6P413	12.690	3.357	0.50	10.66	7.21
FRACTTOUGH6P414	12.695	3.363	0.50	10.66	6.27
FRACTTOUGH6P415	12.695	3.350	0.50	10.66	6.23
FRACTTOUGH6P416	12.690	3.340	0.50	10.66	8.53
FRACTTOUGH6P417	12.690	3.300	0.50	10.66	3.64
FRACTTOUGH6P418	12.695	3.333	0.50	10.66	8.80
FRACTTOUGH6P419	12.695	3.327	0.50	10.66	5.41
FRACTTOUGH6P420	12.700	3.340	0.50	10.65	6.52
Average					6.52

TABLE IX
Fracture Toughness Data from Tests Conducted at 762 cm/min Loading Rate on P4

Specimen ID	Avg. width, W (mm)	Avg. thickness, b (mm)	a/W	$f(a/W)$	K_{IC} (MPa $m^{1/2}$)
FRACTTOUGH300P421	12.700	3.283	0.50	10.65	14.59
FRACTTOUGH300P422	12.695	3.287	0.50	10.66	15.17
FRACTTOUGH300P424	12.690	3.280	0.50	10.66	13.76
FRACTTOUGH300P425	12.700	3.263	0.50	10.65	14.87
FRACTTOUGH300P426	12.690	3.230	0.50	10.66	13.14
FRACTTOUGH300P427	12.700	3.230	0.50	10.65	14.87
FRACTTOUGH300P428	12.695	3.203	0.50	10.66	9.98
FRACTTOUGH300P429	12.695	3.200	0.50	10.66	14.42
FRACTTOUGH300P430	12.690	3.200	0.50	10.66	11.94
FRACTTOUGH300P431	12.690	3.183	0.50	10.66	13.36
Average					13.61

crease in the fracture toughness of the composite material.

CONCLUSIONS

While many scientists have investigated the fracture toughness properties in various continuous fiber-reinforced composite materials, there is no literature available on the fracture toughness properties of random-chopped fiber-reinforced composite materials. The fracture toughness of four random-chopped carbon fiber composite material systems (P4, HexMC, CCS150, and CCS100) were determined and reported in this manuscript. The fracture toughness of the HexMC composite was found to be the highest followed by CCS150, CCS100, and P4 in the order of decreasing fracture toughness. There is also no literature available on the effect of loading rate on the fracture toughness properties of random-chopped fiber-reinforced composite materials. Tests were conducted on randomly oriented chopped carbon fiber P4 composite materials to evaluate the strain rate dependence of their fracture toughness. The test program considered three loading rates: 0.15, 15.2, and 762 cm/min. The fracture toughness of the P4 composite was found to increase with increasing loading rate from 0.15 to 762 cm/min. Explanations for all the observed trends and results have been detailed in the manuscript. Further studies of the strain rate effects on the fracture toughness properties of random-chopped fiber composites are suggested wherein the random fiber composites are subjected to loads at even higher rates than those reported in this manuscript.

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