Impact behaviour of auxetic Kevlar®/epoxy composites

To cite this article: S Yang et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 254 042031

View the article online for updates and enhancements.

Related content
- Mode I Fracture Characterization of Banana Fibre Reinforced Polymer Composite
  Prem Kumar Naik, Neelakantha V Londe, B Yogesh et al.
- Design, fabrication and structural optimization of tubular carbon/Kevlar®/PMMA/graphene nanoplate composite for bone fixation prosthesis
  F Nasiri, S Ajeli, D Semnani et al.
- Fracture Toughness of YBaCuO Prepared by MPMG Process
  Hiroyuki Fujimoto, Masato Murakami, Terutsugu Oyama et al.
Impact behaviour of auxetic Kevlar®/ epoxy composites

S Yang1, V B Chalivendra1 and Y K Kim2

1University of Massachusetts Dartmouth, Department of Mechanical Engineering, 285 Old Westport Road, Dartmouth, MA 02747 USA
2University of Massachusetts Dartmouth, Department of Bioengineering, 285 Old Westport Road, Dartmouth, MA 02747 USA

E-mail: ykim@umassd.edu

Abstract. Experimental study was performed to investigate fracture and impact properties of novel Auxetic Kevlar® laminated composites. For comparison, standard Kevlar® woven composites with and without polyurethane surface treatment were also considered in this study. For these three composites, short nylon fibers of two different fiber lengths and three different fiber densities were flocked between laminates. Vacuum infusion process along with optimized compaction was employed to fabricate composites. The double cantilever beam configuration was used to investigate the fracture properties. The Auxetic Kevlar® composites showed a significant improvement of 225% in fracture toughness compared to regular woven Kevlar® composites. Furthermore, the initiation toughness was increased by 577% with the application of flocking in Auxetic Kevlar®. During impact testing, the Auxetic Kevlar® reinforced composites showed a significant reduction in damaged area compared to woven counterpart. On the other hand, the reduction in damaged area influenced the reduction in impact energy absorption.

1. Introduction

In this study, an experimental work was conducted to understand fracture and impact performance of auxetic Kevlar® laminar composites. To have a valid comparison, plain weave Kevlar® composites with and without polyurethane (PU) surface treatment were also fabricated and characterized. Thus, three types of preforms used: plain weave untreated (K), plain weave PU treated (P) and auxetic warp knit (AK). In addition, inter-laminar z-axis reinforcement with short nylon flock fibres was utilized to investigate the efficacy of various flocking parameters such as flock fibre length and fibre density on fracture and impact properties of these laminar composites. Vacuum infusion process along with optimized compaction technique was used to fabricate the laminar composites. The double cantilever beam (DCB) test was used to characterize the fracture properties.

2. Experimental

2.1. Materials

The 2000/2120 series amine-cured epoxy resin system supplied by FiberGlast (Brookville, OH) was used as matrix material. For reinforcement preforms, plain weave Kevlar® fabric of 3000-denier Kevlar® fibres (shown in Figure 1(a)) and novel auxetic Kevlar® fabrics fabricated in UMass Dartmouth Fabric Development Lab using 200-denier Kevlar® fibres (Figure 1(b)) were used [1].
The 3-denier nylon short flock fibres (0.5mm, and 1.2mm long) were used for interlaminar z-axis reinforcement (Claremont Flock Inc., Leominster, MA). A polyurethane spray (Minwax Company, NJ) was used for surface treatment on woven Kevlar® fabric to improve the adhesion between laminar layers.

2.2 Fabrication of composites and Mode I Fracture Characterization
Fabrication of composites and characterization: Surface treatment, interlayer flocking and laminar stacking were performed as described in Yang [2]. Vacuum infusion process was employed to fabricate laminated composites. Mode I fracture properties were determined with double cantilever beam (DCB) method (ASTM D 5528).

2.3. Impact characterization
A custom built high-speed projectile impact testing system [3] was employed to determine the energy absorption and damage of composites. Details of the test setup are discussed in the reference. A compressed helium gas was used in a tank to shoot a projectile in a 3m long Stainless steel barrel. The projectile consists of a 45 caliber full metal jacket bullet of 230 grain (14.9 g) (supplied by Hornady, Grand Island, NE) in a plastic sabot. A laser-photodiode detector placed at the end of the barrel measures the input projectile velocity. A standard shooting chronograph, (an Alpha Chrony model manufactured by Shooting Chrony, Inc. Amherst, NY) was used to measure the projectile velocity after penetrating through the test specimen.

Chronograph was calibrated with the help of laser-photodiode and the velocity measurements of chronograph were later adjusted using the calibration correction factor under no specimen conditions. Maximum gas pressure 1379 kPa (200 psi) was employed to test the composite specimens. The resulting projectile velocity at maximum pressure is 167 m/s. Lower velocities were tried, but the projectile did not pass through woven fabric Kevlar® composites. Hence results are reported only for situations of projectile penetration so that energy absorption can be determined. The specimens of 101.6mm square area were held under fixed boundary conditions on all four sides for impact loading conditions. Energy absorption during penetration of projectile was measured using the change in kinetic energy of the projectile.

Damage area of a projectile impacted specimen was determined with the help of the image analysis package of Matlab® programming language.

3. Results and discussion

3.1. Mode I fracture toughness
The fracture initiation energy (G\text{IC}) of all three types of composites with no flocking and flocking conditions is shown in Figure 2. For a non-flock condition, the G\text{IC} value of auxetic Kevlar® composites are about 125% more than polyurethane treated woven Kevlar® composites, however the values are about 225% more than untreated woven Kevlar® composites. Again for a no-flocking
situation, polyurethane treatment improved the $G_{IC}$ value by 43% compared to untreated woven Kevlar® composites.

In general, flocking increased fracture initiation energy significantly for all three types of composites. The increase is much higher for auxetic Kevlar® composites compared to other two types. In case of woven Kevlar® composites, flocking of 1.2mm and 600 fibers/mm$^2$ case provided maximum increase in $G_{IC}$ value by 122% compared to an unflocked situation. For 600 fibers/mm$^2$, the increase is only 5% for 1.2mm, when it is compared with 0.5mm case. It leads to a conclusion that the increase in flock length does not make for a significant improvement in $G_{IC}$ value. Moreover, the $G_{IC}$ values decreased for 400 fibers/mm$^2$ when flock length increased from 0.5mm to 1.2mm. It seems for lower flock densities, for better $G_{IC}$ values, the ideal flock length should be a smaller value.

For auxetic Kevlar® composites of 0.5mm fiber length, as the fiber density increased from 200 fibers/mm$^2$ to 400 fibers/mm$^2$, the $G_{IC}$ value increased by 78%. However, with the further increase in fiber density to 600 fibers/mm$^2$, the $G_{IC}$ value decreased by 37%. Given error bars for 1.2mm of all fiber densities in auxetic composites, the $G_{IC}$ value did not change significantly.

Figure 3 shows the R-curves for all possible configurations of flocking for both untreated and treated woven Kevlar® composites. As given in Figure 3(a), the propagating fracture energy (G) is not significantly affected by the flocking except for 400 fibers/mm$^2$. There is a significant increase in G value as the crack length increases. It can be noted that similar increase in $G_{IC}$ value is achieved for 400 fibers/mm$^2$ compared to other two fiber densities. It seems 400 fibers/mm$^2$ is optimum fiber density and any further increase in fiber density did not improve the both $G_{IC}$ and G value. G values for polyurethane (PU) treated woven composites of 0.5mm flock length are given in Figure 3(b). PU treatment has not made any improvement in G values for a no-flock condition when compared to an untreated non-flock composite shown in Figure 3(a). G values improved significantly for all flock situations when compared to a unflocked condition. However there is no significant change in G value with change in fiber density. Figure 3(c) shows the G values of propagating crack for an untreated woven composites flocked with 1.2mm long. There is no significant difference between unflocked and flocked ones for this scenario except for fiber density of 600 fibers/mm$^2$ with a slight increase in G value for most of the crack growth. G values for propagating crack of PU treated woven Kevlar® composite of 1.2mm long flocked fibers are shown in Figure 3(d). Again there is no major difference between unflocked and flocked ones for this scenario except for fiber density of 200 fibers/mm$^2$ with significant increase in G value for most of the crack growth.
Figure 3. R-curves for woven composites with (a) untreated condition, flock length of 0.5mm, (b) PU treated, flock length of 0.5mm, (c) untreated, flock length of 1.2mm, and (d) PU treated, flock length of 1.2mm.

Figure 4. Impact energy absorption for all three types of composites.
3.2. Impact energy absorption

The impact energy absorption (IEA) of all three types of composites with and without flocking of two extreme different fiber densities (200 and 600 fibers/mm\(^2\)) and two different flock fiber lengths (0.5mm and 1.2mm) at projectile velocity of 167m/s is shown in Figure 4.

For untreated woven Kevlar® composites, the highest energy absorption was achieved for a non-flock condition. Additional flocking did not improve the IEA for all flocking scenarios. In fact, IEA was decreased at maximum by 44% for the case of fiber length of 1.2mm and fiber density of 200 fibers/mm\(^2\). Although there is some gain in IEA for composites made with fiber length of 1.2mm and fiber density of 600 fibers/mm\(^2\), but it is still less than the IEA value of a non-flock case.

For PU treated woven composites, both unflocked and flocked cases showed less IEA value compared to an un-flocked case of woven Kevlar® composites. Similar to woven composites, PU treated woven composites also showed the same trend of decrease in IEA value with flocking except for the case of fiber length of 1.2mm and fiber density of 600 fibers/mm\(^2\). There is a slight increase in IEA for this case, but given error bars, the increase is not significant.

In the case of auxetic Kevlar® composites, the IEA values followed a different trend to that of the other two cases. The IEA values increased with the addition of flocking. The increase is around 55% for the case of flock fiber length of 1.2mm and fiber density of 600 fibers/mm\(^2\) when compared to a non-flock case. This case is comparable to a non-flock woven Kevlar® composite IEA value with only 5% reduction.

To account for differences in thickness of test specimens on impact energy measurements, specific energy absorption is determined by normalizing with specific gravity of the respective composites as shown in Figure 5. Although most of the composites showed similar trend to that of energy absorption shown in Figure 4, specific energy absorption of auxetic Kevlar® composites with 1.2mm flock fibers at 600 fibers/mm\(^2\) showed higher value than that of woven Kevlar® composites with no flocking.

![Figure 5. Specific Impact energy absorption for all three types of composites](image_url)
### 3.3 Damage area

The damage areas on both sides (impact and exit) of composite panel for all three types were determined with image analysis. For untreated woven Kevlar® composites, the damage area is around 98cm$^2$ on both front (impact) and rear (exit) side of panels.

![Damage Area](image)

**Figure 6.** Damage area (a) on the front side of the composite panel, and (b) rear side of the composite panel, for all three types of composites

Damage area decreased significantly on front side of the panels as shown in Figure 6(a) with the flocking, and the maximum decease of about 88% was observed for the case of flock fiber length of 0.5mm and fiber density of 200 fibers/mm$^2$. Although the damage area on the rear side of the specimen shows similar trend as shown in Figure 6(b), it was significantly higher for most of the cases except for composites made from a flock fiber length of 0.5mm and fiber density of 200 fibers/mm$^2$. For both flock fiber lengths, as the flock fiber density increased from 200 to 600 fibers/mm$^2$, the damage area increased significantly on both sides of the composite panel. For PU treated woven composites, for a non-flock situation, the damage area decreased by about 42% when compared to untreated woven composites. With flocking, the damage area decreased on the front side of the panels,
however, the damage area increased considerably. Again similar to the untreated case, the damage area increased as the fiber flock density increased from 200 to 600 fibers/mm² on both sides for both fiber flock lengths.

In the case of auxetic Kevlar® composites, the maximum damage area is about 5cm² on both sides of the panels. Flocking did not change the damage area significantly on both sides. Auxetic Kevlar® showed great promise for damage tolerance under impact loading conditions.

4. Conclusions
A comprehensive experimental study was conducted to understand fracture and impact behaviour of novel auxetic laminated composites. For comparison, its properties were compared with both untreated and PU treated woven Kevlar® composites. Following are the major conclusions of the study:

- Overall, z-directional inter-laminar reinforcement with short nylon fibers improved fracture initiation toughness for all three types of composites investigated.
- Under no-flocking conditions, auxetic composites shows about 225% higher fracture toughness than untreated woven composites, and about 126% more than treated woven composites.
- Under flocking conditions, auxetic composites showed about 220% more fracture toughness than untreated woven composites and 200% more than treated woven composites.
- Crack was arrested in auxetic composites and later deflected into laminate layer, whereas crack propagated along interface of matrix and laminar layer in both untreated and treated woven composites.
- Untreated woven composites with no flocking showed superior impact energy absorption compared to all other types of composites. Flocking decreased the energy absorption values significantly for both untreated and treated woven composites. However, auxetic composites with high flock length and density approached the maximum impact energy absorption of the woven composites.
- Front and rear damage areas of both untreated and treated woven composites decreased significantly with flocking under impact loads, however the auxetic composites showed a very low damage area compared to both type of composites.

Acknowledgments
Authors wish to acknowledge encouragement and help from Dr. Armand F. Lewis and Dr. Samuel Ugbolue of Bioengineering Department at the UMass Dartmouth, and financial support from the University of Massachusetts Office of Technology and Commercial Venture.

References
[1] Ugbolue S C, Kim Y K, Warner S B, Fan Q, Yang C-L, Kyzymchuk O, Feng Y, Lord J 2011 The formation and performance of auxetic textiles, Part II, geometry and structural properties, The Journal of Textile Institute 102 pp424-433
[2] Yang S 2016 Fracture and Impact Characterization of Auxetic Kevlar® Laminated Composites MS Dissertation (Dartmouth: University of Massachusetts Dartmouth)
[3] Héctor O C 2010 Projectile impact behaviour of flock fibre z-reinforced composites MS Dissertation (Dartmouth: University of Massachusetts Dartmouth)