Effect of Laminate Geometry on Impact Performance of Aramid Fiber/Polyethylene Fiber Hybrid Composites

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ABSTRACT:: One-layer and two-layer hybrid composites were fabricated using open leaky mold method in order to examine the effect of structural geometry on impact performance of aramid fiber/polyethylene (PE) fiber hybrid composites. The impact property of interply hybrid composites was compared with that of intraply hybrid composites with respect to impact mechanism and deformation extent. In addition, the delamination area of two hybrid composites was considered for correlation with impact properties. In one-layer composites, two intraply hybrids exhibited the different characteristics in impact mechanism and deformation shape. The laminate T absorbed most of impact energy through large deformation of PE fibers with an elliptical damage shape. On the other hand, the laminate R showed the higher impact energy because both aramid and PE fibers contributed to the absorption of impact energy with a round damage zone. In case of two-layer composites, interply hybrid composites exhibited higher impact energy than intraply hybrid composites. The interply hybrids absorbed the impact energy through deformation process such as fiber pullout and delamination, and impact energy was well correlated to delamination area. The impact energy of intraply hybrid composites was primarily dominated by full exertion of deformation in PE fiber rather than delamination process. © 2000 John Wiley & Sons, Inc. J Appl Polym Sci 75: 952–959, 2000

Key words: laminate geometry, impact performance, interply and intraply hybrid composite, delamination area, CTBN modified matrix

INTRODUCTION

The term "hybrid composite" is used to denote the material that contains two or more types of fibers in a matrix.[1–3] Over the last decade, these materials have been focused on the material development and their applications have increased rapidly for a number of important reasons.[4–6] The polyethylene (PE) fiber-reinforced composite is an attractive material because of its high-impact resistance and it is much used in military applications such as helicopters and body armor. However, PE fibers have poor adhesion to polymer matrix due to the chemical inertness and have the limitation for structural applications. To compensate for this defect, the aramid fiber is hybridized in PE fiber-reinforced composite as a secondary reinforcing fiber. One of the most important purposes using aramid fiber/PE fiber hybrid composites is to combine the good mechanical property of aramid fiber with the excellent impact resistance of PE fiber.[7,8]

The hybrid composites can be largely classified as interply and intraply hybrid composite according to the geometric pattern of laminate.[9–11] In interply hybrid composites, two kinds of fabrics in which each fabric consists of a kind of fiber are laminated with a change of stacking sequence. On

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the other hand, each fabric of intraply hybrid composites consists of two or more kinds of fiber. Each hybrid composite exhibits the different behavior in mechanical response, stress transfer, and failure mechanism. This may be attributed to difference in structure and failure mode of two hybrid composites. Therefore, the mechanical properties of interply and intraply hybrid composites should be systematically studied for the applications to the structural components. Among the mechanical properties, the impact performance is especially important because its information is applied to the real system and makes the new material design possible. In interply hybrid composites, the influence of stacking sequence on impact properties of hybrids should be systematically clarified. The position and volume ratio of each component in the hybrid composites can act as determining factors in the change of the impact performance.[12–15] On the other hand, the intraply hybrid fabric has a peculiar structure in which warp yarn and weft yarn consist of the different fibers, respectively. Each fiber within a fabric has different stress distribution and load-transfer capability, and deformation of each fiber is affected by adjacent fibers. Moreover, deformation extent in warp and weft direction is different because the impact load cannot be dispersed uniformly into warp and weft direction. These heterogeneous condition and dissimilar environment may induce the different impact performance to interply hybrid composites. However, the impact performance of two hybrid composites has not been well understood with respect to impact mechanism and deformation extent.

In this study, one-layer and two-layer aramid fiber/PE fiber hybrid composites are prepared to compare the impact performance of interply and intraply hybrid composites. The impact mechanism of intraply hybrid composites is investigated with respect to load transfer at crossover points. The delamination area of interply and intraply hybrids is also considered for correlation with impact properties.

EXPERIMENTAL

Materials

The aramid fiber used in this study was Kevlar-29 from E. I. Du Pont de Nemours in the form of a 4800 denier and 480 filament yarn. The PE fiber was Spectra-900 from Allied Signal Co. (Morristown, NJ, USA) in the form of a 3000 denier and 300 filament yarn. The fabric used for intraply hybrid composites was the plain type of aramid fiber and PE fiber. Two different intraply fabrics were used. The first fabric (INTRA11) was composed of aramid fiber in warp and PE fiber in weft, so that the volume ratio of aramid fiber to PE fiber was 1:1. The second fabric (INTRA31) was composed of aramid fiber in warp, and aramid and PE fiber by turns in weft, so that the volume ratio of two fibers was 3:1. The structure of two intraply fabrics is shown in Figure 1. The matrix resin was styrene-based XSR-10 vinylester resin supplied by Sewon Chemical Co. (Seoul, Korea). This resin was modified with carboxyl terminated butadiene acrylonitrile (CTBN) rubber to improve the impact properties. The styrene contained in vinylester resin was used as a cross-linking agent, and dibenzoyl peroxide (BPO) was used as an initiator. The acetone was used as a solvent for the initiator and viscosity-reducer of the matrix resin. The physical properties of Kevlar-29, Spectra-900, and vinylester resin are given in Table I.

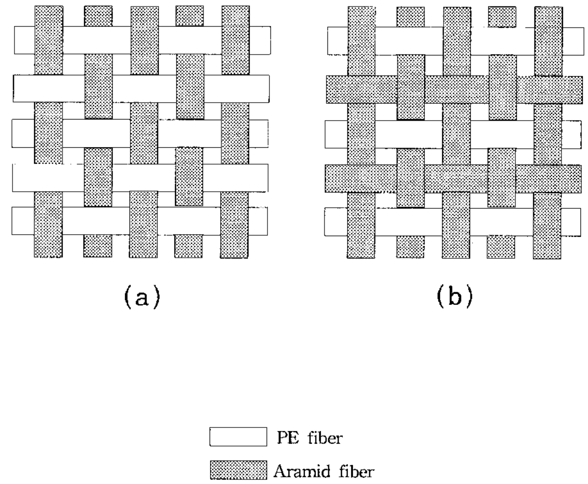

Figure 1 The structure of two intraply fabrics: (a) INTRA11; (b) INTRA31.

Prepreg Preparation

The vinylester resin, BPO, and acetone were mixed in the weight ratio of 100:2:10. Each fabric was well impregnated into a solution of this mixture by hand roller. The resin-impregnated fabrics were aged for two days at room temperature in a drying hood for thickening of the resin.

Composite Manufacturing

The composites were made using open leaky mold method. All composites were then cured in a hot

Table I Physical Properties of Kevlar-29, Spectra-900, and Vinylester Resin

Physical Properties	Kevlar-29	Spectra-900	Vinylester
Density (g/cm^3)	1.44	0.97	1.15
Tensile modulus (GPa)	62.00	117.30	3.71
Tensile strength (MPa)	2760	2500	63
Maximum strain (%)	4.00	3.50	6.30

press for 20 min at 43°C and 50 min at 90°C at a pressure of 7 MPa (1000 psi). The total volume fraction of fiber in all laminates was about 60%. The one-layer and two-layer hybrid composites were prepared to compare the impact performance of interply and intraply hybrids. In interply hybrid composites, various hybrid configurations were prepared by interleaving plies of aramid and PE fabric with the different stacking sequence. The intraply hybrid composites were laminated with two different stacking sequences of 0/0 and 0/90. **A** designated the aramid fabric, **P** denoted the PE fabric, **T** the INTRA11 fabric, and **R** the INTRA31 fabric. The intraply laminate **TT0** meant the stacking sequence of 0/0 and the laminate **TT90** meant the stacking sequence of 0/90.

Impact Property

The impact properties of hybrid composites were conducted using a Radmana ITR-2000 driven dart impact tester. The laminate was clamped horizontally between two plates with an inner diameter of 7.5 cm. The impact tip was hemispherical type with the size of 1.76 cm. The pressure of nitrogen gas was varied to give a range of incident velocity and energy. The impact velocity was fixed at 4.0 m/s (velocity unit). Load-displacement curve was recorded and initiation energy, propagation energy, and total energy were calculated. The total impact energy was defined as the sum of the energy absorbed until the maximum load (initiation energy) and the energy absorbed after the maximum load (propagation energy). The dimension of the test specimens was 10 cm × 10 cm.

Damage Shape Analysis

The deformation shape of hybrid composites was analyzed using manual camera after impact of the specimens. Both impacted surface and back surface of the composites were observed to examine the relationship between the damaged shape and the absorbed impact energy.

Delamination Area Calculation

After impact test, the delamination area of hybrid composites was calculated for the correlation to impact energy. The delamination area of each layer was determined by the process of penetrant injection and de-plying. The stamp ink as a penetrant was used to enhance the identification of delaminated areas. The deformed region of the composite was easily seen due to the red color of the stamp ink. The penetrants used prior to deplying were left in all parts of the damage of laminate. After penetrant injection, the laminate was separated into individual plies. The delamination area of each ply was measured by tracing the damage area onto positron emission tomography (PET) film and manually measuring the weight of film.

RESULTS AND DISCUSSION

The difference in structure and failure mode of two hybrid composites, i.e., interply and intraply, may result in the change of mechanical properties. Especially, impact properties were emphasized considering stacking sequence and failure mode. One-layer and two-layer hybrid composites were prepared to investigate the difference in impact behavior of two composites. Table II summarizes the impact properties of one-layer hybrid composites. The laminate P shows the highest maximum load and total energy, but the laminate A exhibits the lowest maximum load and total energy. This is due to the superior toughness and damage tolerance of PE fiber. The laminate P displays the large proportion of initiation energy, indicating that much impact energy is absorbed before maximum load. In the laminate T and laminate R, the maximum load and total energy lie in value between laminate A and laminate P. The PE fibers at intraply fabric play a major role in dispersing the impact energy continuing to bear the applied load.

Table II Maximum Load and Impact Energies of One-Layer Hybrid Composites

	Maximum Load (N)	Initiation Energy (J)	Propagation Energy (J)	Total Energy (J)
A	1915	5.78	8.55	14.33
T	1719	18.72	5.54	24.26
R	2154	26.27	10.43	36.70
P	2562	36.55	7.48	44.03

The impact behaviors of hybrid composites can be explained through the load-displacement curves during the impact. The load-displacement curves of one-layer hybrid composites are shown in Figure 2. The laminate A exhibits the highest initial slope and the lowest displacement at break. This is caused by low impact resistance of aramid fibers, which possess high tensile strength and modulus but low fracture strain. The steep initial slope is a major characteristic of the composite with brittle failure. In laminate P, the maximum load and displacement at break are maximized due to high elongation property of PE fiber. The laminate bears the impact load up to higher displacement, and the load drops rapidly after maximum load. The impact response of the composite appears to be dominated by the initiation step and a major portion of the impact energy is dissipated before this laminate experiences the maximum load. The intraply hybrids exhibit higher displacement at break than laminate A due to the presence of PE fibers within fabric. The presence of PE fibers changes the shape of load-displacement curve and this indicates that there is the change in energy absorption mode. The laminate R, which contains higher content of aramid fiber, displays superior impact resistance to the laminate T. This is due to the difference in failure mechanism and will be explained in detail later.

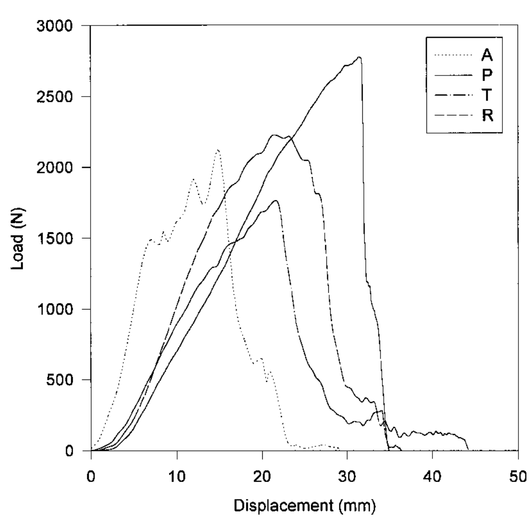

Figure 2 The load-displacement curves of one-layer hybrid composites.

Figure 3 represents the photographs showing the change in fracture surface of one-layer composites after impact test. Figure 3a–c show the back surfaces of the laminate P, laminate T, and laminate R, respectively. The composite P exhibits the uniform deformation in overall laminate through the formation of dome. The excellent impact toughness of PE fiber enhances the perforation resistance of the composite, leading to a considerable degree of plastic deformation. In composite T, there is a slippage of PE fibers toward impact point and bundle of PE fibers exists around perforated point. This indicates that deformation of composite occurs primarily in the PE fiber direction. On the other hand, the composite R shows aramid fiber breakages near the impact point and there is little slippage of PE fibers. This means that the composite has a little brittle nature and impact energy is dispersed uniformly into both aramid and PE fiber.

Judging from above results, the model of failure mechanisms for intraply hybrids is schematically represented in Figure 4. The woven fabric has the crossover points at which warp yarn and weft yarn intersect as a consequence of the weaving process. A majority of impact energy is absorbed through fiber bridging at crossover points, and thus the load transfer at crossover point plays a significant role in determining the impact performance of composite. Therefore, the difference of impact energy in laminate T and laminate R can be explained by comparing load transfer at crossover point and deformation extent. In laminate T, the concentrated stress at crossover point is dispersed respectively into four directions on impact loading (Fig. 4a). However, the load transfer is more pronounced in PE fiber direction due to its excellent toughness, which leads to large

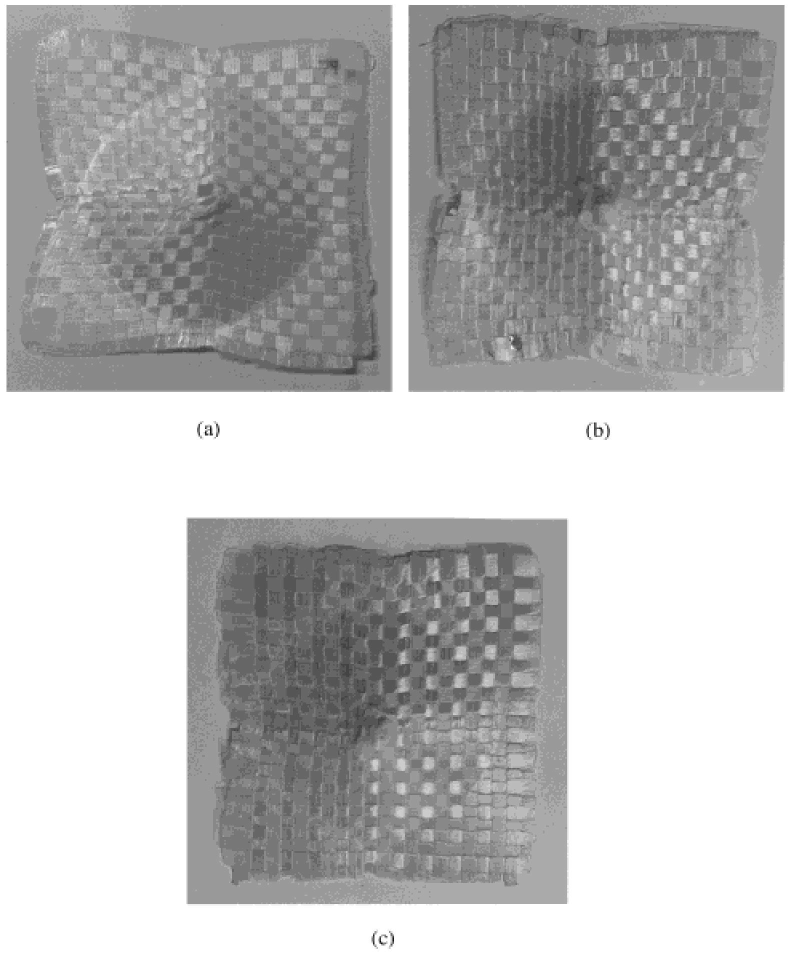

Figure 3 The photographs showing the change in fracture surface of one-layer composites after impact test: (a) laminate P, (b) laminate T, and (c) laminate R.

deformation into direction "①". The load along aramid fiber is again dispersed at crossover point "a", and load transfer occurs primarily in PE fiber direction. However, the deformation extent in direction "②" is smaller than that in direction "①". The deformation in PE fiber direction reduces rapidly as it becomes distant from impact point. As a result, the deformation shape of laminate T resembles the ellipse showing large deformation in the PE fiber direction. Most of impact energy is absorbed through deformation of PE fibers within damage zone, and the contribution of aramid fiber to absorption of impact energy is very low. In the case of laminate R, the load transfer at impact point is uniform in four directions (Fig. 4b). As the load propagates along aramid fiber, the successive load transfer occurs at new crossover point "a". It can be predicted that the load is dispersed mainly in the PE fiber direction. In contrast with the prediction, however, the deformation extent in direction "②" is not large compared with that in direction "①" because adjacent aramid fibers restrict the deformation of PE fiber. The load transfer at other crossover points also proceeds in this manner. From these results, it is clear that the deformation shape of laminate R is a round form nearly. Furthermore, on impact loading both aramid fiber and PE fiber contribute to dispersion of impact energy and the laminate becomes more or less stiff and brittle. In a comparison of laminate T and laminate R, two laminates exhibit the different characteristics in role of each fiber and deformation shape. Compared with laminate T, the laminate R shows higher impact energy because both aramid fiber and PE fiber absorb the impact energy with uniform and wide deformation zone.

The maximum load and impact properties of two-layer hybrid composites are represented in Table III. The impact energy of interply and intraply hybrids is higher than that of the laminate

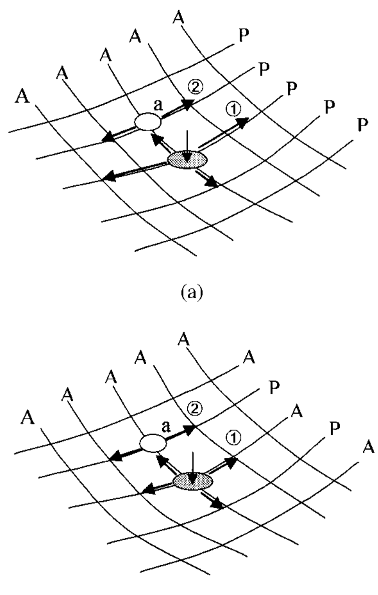

Figure 4 The model of impact mechanism for intraply hybrid composites: (a) laminate T; (b) laminate R.

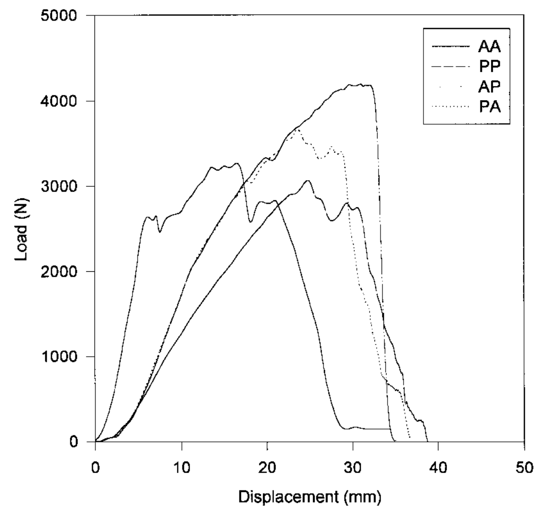

Figure 5 The load-displacement curves of interply hybrid composites.

PP. This is not consistent with the results of one-layer hybrid composites. The load-displacement curve of laminate PP is almost similar to that of laminate P with respect to maximum load and displacement at break (Fig. 5). This means that the addition of a PE layer to laminate P does not double the impact energy of composite due to the enhanced laminate stiffness. The PE layer at back surface restrains the deformation of PE layer at impacted surface, and thus the increment of impact energy is small in laminate PP. In interply hybrid composites, much impact energy is dissipated at the interface between the aramid and PE layer due to easy separation of laminas. The fiber pullout and delamination are a major mechanism to absorb the impact energy in this process. The impact energy of hybrid composites is larger than the sum in impact energy of laminate A and laminate P. The additional portion of impact energy is attributed to absorption at aramid-PE layer interface. Considering the stacking sequence, the laminate AP displays higher impact energy than laminate PA. This is caused by the fact that in laminate AP the PE layer at back surface can deform and deflect fully, but the PE layer of laminate PA has the restricted deformation by adjacent aramid layer. This is also reflected by load-displacement curves. The laminate AP bears impact load up to higher displacement through the deformation of PE layer (Fig. 5). These results can be correlated to data of delamination area in Table IV. The laminate PP shows the low delamination area and laminate AP exhibits higher delamination area than laminate PA. On the other hand, intraply hybrid com-

Table III Maximum Load and Impact Energies of Two-Layer Hybrid Composites

	Maximum Load (N)	Initiation Energy (J)	Propagation Energy (J)	Total Energy (J)
AA	3327	12.01	46.42	58.43
PA	3782	48.37	24.36	72.73
AP	3971	72.87	10.68	83.55
TT0	2997	44.43	17.53	61.96
TT90	3159	47.39	23.63	71.02
RR0	3901	64.80	14.79	79.59
RR90	4249	68.75	7.42	76.17
PP	3160	40.46	22.38	62.84

posites exhibit very low delamination area in spite of high impact energy. Compared with interply fabric, intraply fabric has the low deformation area because deformation of PE fibers is restrained by adjacent aramid fibers. Moreover, load transfer at crossover points is concentrated in the PE fiber direction and the impact load is not dispersed effectively into overall laminate. Although the delamination that is related to overall deformation of lamina decreases, the deformation of PE fibers is maximized due to concentration of impact load. As a result, the impact energy of intraply hybrid composites is primarily dominated by full exertion of deformation in PE fiber rather than delamination of laminate. The laminate RR0 and RR90 exhibit higher maximum load and total energy than counterpart laminate TT by the same reason discussed in laminate T and R. The stacking sequence also has an effect on the impact behavior of composites. The laminate TT90 exhibits higher impact energy than the laminate TT0. This is due to the difference in deformation extent. The laminate TT0 exhibits an elliptical damage zone represented in laminate T and the dispersion of impact energy occurs mainly in PE fiber direction. In 0/90 lay-up, however, the PE fiber directions of two laminas are perpendicular to each other and the deformation along the PE fiber is formed uniformly in all directions. As a result, the delamination area of laminate TT90 is larger than that of laminate TT0 (Table IV). These results are confirmed by load-displacement curves. The impact energy of laminate TT90 is absorbed up to higher displacement showing the low initial slope (Fig. 6). On the other hand, laminate RR0 and laminate RR90 show the similar impact energy and delamination area. As discussed in Figure 4, laminate R has an intrinsic brittle nature and deformation occurs in both aramid fiber and PE fiber with wide damage area. Therefore, the deformation extent of laminate RR is not affected largely by stacking sequence.

Table IV Delamination Area of Two-Layer Hybrid Composites

	Delamination Area (cm^2)
AA	54.23
PA	45.62
AP	59.60
TT0	19.13
TT90	27.96
RR0	24.28
RR90	25.75
PP	39.74

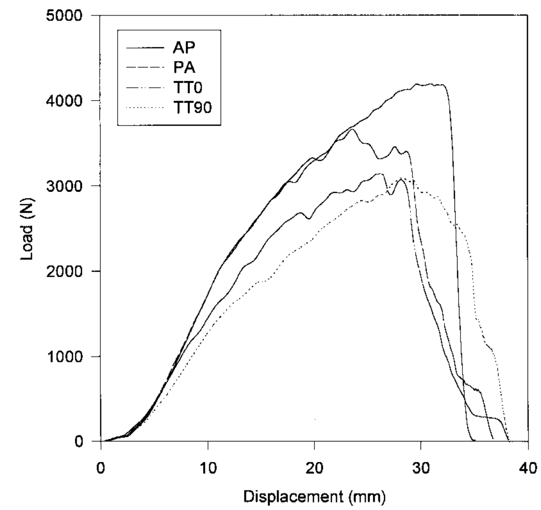

Figure 6 The load-displacement curves of intraply hybrid composites.

Consequently, interply and intraply hybrid composites exhibit the different characteristics in impact mechanism and deformation extent. In the interply hybrids, the fibers at impact point transfer uniformly the applied impact load to adjacent fibers and the overall region of fabric attributes to absorption of impact energy. The laminate absorbs impact energy through deformation process such as fiber-matrix debonding, fiber pullout, and delamination. Therefore, the delamination area of laminate is considerable through the dome formation and the impact energy is well correlated to the delamination area. In the intraply hybrids, however, the PE fibers at impact point can not deform fully due to restraint of adjacent aramid fibers, and the applied load can not be transferred effectively to next PE fibers. The deformation of laminate becomes local and the impact load is not dispersed into overall laminate. As a result, the intraply hybrid composites absorb most of impact energy through full exertion of deformation in PE fiber rather than delamination process. The impact response of interply and intraply hybrid composites is compared in Figure 6.

CONCLUSIONS

Aramid fiber/PE fiber hybrid composites were fabricated to examine the effect of laminate geometry on impact performance of hybrid composites. The impact properties of interply and intraply hybrid composites were compared with respect to impact mechanism and deformation extent. In one-layer composites, two intraply hybrids exhibited the different characteristics in load transfer at cross-over points and deformation extent. The laminate T absorbed most of impact energy through large deformation of PE fibers with an elliptical damage shape. The bundle of PE fibers existed around perforated point with a slippage of PE fibers toward impact point. In case of laminate R, load transfer into PE fiber direction was restricted by adjacent aramid fibers, and both aramid and PE fiber contributed to the absorption of impact energy with a round damage zone. The laminate exhibited aramid fiber breakages near the impact point with little slippage of PE fibers. In case of two-layer composites, interply hybrid composites exhibited higher impact energy than intraply hybrid composites. The impact energy of interply hybrid composites was mainly absorbed through delamination, and thus impact energy was well correlated to delamination area. On the other hand, the intraply hybrid composites absorbed a majority of impact energy by full exertion of deformation in PE fiber rather than delamination process.

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REFERENCES

1. Hancox, N. L. Fiber Composite Hybrid Materials; Applied Science Publishers: London, 1981.
2. Woods, D. W.; Hine, P. J.; Ward, I. M. Compos Sci Technol 1994, 52, 397.
3. Dickson, R. F.; Fernando, G.; Adam, T.; Reiter, H.; Harris, B. J Mater Sci 1989, 24, 227.
4. Collings, T. A. Composites 1991, 22, 369.
5. Aronhime, J.; Harel, H.; Gibert, A.; Marom, G. Compos Sci Technol 1992, 43, 105.
6. Murno, M.; Lai, C. P. Z. J Mater Sci 1988, 23, 3129.
7. Park, R.; Jang, J. Polymer Testing 1997, 16, 549.
8. Govaert, L. E.; D'hooghe, E. L. J. C. J.; Peijs, A. A. J. M. Composites 1991, 22, 113.
9. Fariborz, S. J.; Harlow, D. G. J Compos Sci 1987, 21, 856.
10. Fukuda, H.; Chou, T. W. J Appl Mech 1983, 50, 845.
11. Fukunaga, H.; Chou, T. W.; Schulte, K.; Peters, W. M. J Mater Sci 1984, 19, 3546.
12. Duvis, T.; Papaspyrides, C. D. Compos Sci Technol 1993, 48, 127.
13. Jang, B. Z.; Chen, L. C.; Wang, C. Z.; Lin, H. T.; Zee, R. H. Compos Sci Technol 1989, 34, 305.
14. Saha, N.; Banerjee, A. N. J Appl Polym Sci 1996, 62, 1193.
15. Peijs, A. A. J. M.; Venderbosch, R. W.; Lemstra, P. J. Composites 1990, 21, 522.