Ballistic Performance of Polycarbonate/Polyester and Polycarbonate/Styrene-Acrylonitrile Microlayer Sheets

WILLIAM G. KOHLMAN

U.S. Army Natick Research, Development and Engineering Center Natick, Massachusetts 01760-5020

Extruded microlayer sheets of polycarbonate/polyester (PC/PCTG) and polycarbonate/styrene-acrylonitrile (PC/SAN) were tested for ballistic performance. Composition of the microlayer sheets ranged from 60 to 100 percent polycarbonate. The number of layers in the approximately 3 mm thick sheets ranged from one for the blend control samples to 3713 layers in the PC/PCTG sheets. The normalized ballistic test results showed that some samples performed as well as and slightly better than injection molded polycarbonate samples. The failure mechanism was affected by the composition and the number of layers. Increasing composition of polycarbonate and number of layers decreased the percent of brittle failures.

INTRODUCTION

Currently, the material of choice for eye protection is polycarbonate. The impact resistance properties of polycarbonate are outstanding; however, the scratch and chemical resistance of the material are poor. There is a need for a material with good scratch and chemical resistance while improving upon the ballistic impact behavior of polycarbonate.

Recent studies with extruded microlayer sheets have shown that many of the microlayer materials possess mechanical properties superior to the sum of the components (1–4). Im *et al.* found that PC/SAN microlayer sheets with the same thickness showed a brittle to ductile transition corresponding to a sharp rise in the impact strength and elongation at break with increasing polycarbonate content (3). This transition shifted to a lower polycarbonate content with increasing number of layers. The impact strength also increased with the number of layers for a given polycarbonate content.

A component that is chemical and scratch resistant but brittle, could be used to produce a material that has the ballistic resistance approaching or matching polycarbonate while improving other properties over polycarbonate. This work examines extruded microlayer sheets for ballistic performance.

MATERIALS

Extruded sheets of the polycarbonate/poly(cyclohexane-1,4-dimethylene terephthalate) (PC/PCTG) and the polycarbonate/poly(styrene-acrylonitrile) (PC/SAN) microlayer samples were provided by the Dow Chemical Company. The reported grades of polymers in the PC/PCTG sheets are Calibre 200-22 and Kodar 5445. The grades of polymers in the PC/SAN sheets are Calibre 302-22 and Tyril 1000B except for samples 41A and 39B which also contain a different polycarbonate grade XU 73049.03 (11 MFR). *Table 1* gives a listing of the samples with respect to polymer composition, number of layers, and thickness, as well as the ballistic testing results.

EXPERIMENTAL

Ballistic performance was evaluated by testing the sheets according to MIL-STD-662E V_{50} Ballistic Test for Armor (5) using a high-pressure helium gas gun. A 17-grain fragment simulator was used as the projectile. The test plaques were rigidly held in a sample holder made from two 33 cm square, 1.9 cm thick aluminum plates bolted together and placed in a mount. Four 2.5 cm diameter holes in the plates located in the center of each corner quadrant provided for the passage of the projectile through the plaques. After each shot, the sample holder was rotated in its mount to align the next sample. After a set of four shots, the holder was removed from the mount, opened, and the samples repositioned for the next shots. A schematic of the test setup is shown in *Fig. 1*.

Four light screens were used as triggers for timers to record the time-of-flight of the projectile to determine the velocity of the projectile before and after

Table 1. Actual and Normalized V_c and V_{50} Values With Sample Description for the Microlayer Materials.

Sample ID	% Composition Polycarbonate	Second Polymer	Number of Layers	Thickness (mm)	Areal Density (kg/m²)	$V_c \pm ()$ (m/s)	$V_{50} \pm ()$ (m/s)	nV_{c*} (m/s)	nV_{50*} (m/s)
55B	80	PCTG	Blend (1)	2.64	3.18	205 (3)	206 (3)	196	197
49C	80	PCTG	1857	2.57	2.99	191 (8)	195 (2)	192	196
49A	60	PCTG	1857	2.59	3.16	186 (10)	189 (4)	178	181
55A	80	PCTG	3713	1.98	2.70	163 (7)	157 (3)	178	172
53A	60	PCTG	3713	2.72	3.31	200 (7)	202 (9)	184	186
25C	100		1	2.90	3.40	221 (4)	218 (1)	200	198
25B	85	SAN	Blend (1)	2.84	3.36	198 (10)	201 (2)	179	183
25A	70	SAN	Blend (1)	2.95	3.33	125 (14)	146 (25)	108	129
15B	85	SAN	233	2.87	3.36	215 (6)	211 (5)	196	193
13B	70	SAN	233	2.77	3.20	117 (16)	118 (17)	107	108
19C	85	SAN	929	2.84	3.30	205 (4)	204 (6)	189	189
19B	70	SAN	929	2.87	3.31	180 (11)	170 (5)	164	155
41A	80	SAN	1857	1.35	1.53	117 (5)	117 (3)	193	191
39B	70	SAN	1857	1.40	1.59	94 (10)	101 (8)	167	172
Injection molded	100		1	3.20	3.99	221 (3)	218 (6)	170	168
Injection molded	100		1	1.60	2.01	136 (4)	130 (6)	187	180

*V_c and V_{50} normalized to a 3 kg/m² areal density.

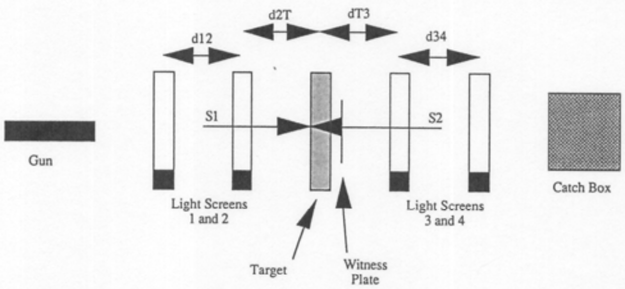

Fig. 1. Diagram of ballistic test setup.

impact. The timers recorded the time-of-flight between screens 1&2, 2&3, 3&4, and 1&4 as a check. From measurements of the distance between each of the screens and target, and the time-of-flight between screens 1&2 and 3&4, the velocities at the midpoint between each set of screens can be determined. The distances from the midpoint of screens 1&2 and 3&4 to the target are referred to as S1 and S2, respectively. The striking and residual velocities were determined by taking air resistance into account over S1 and S2 as shown in *Eqs 1* and *2* (6)

$$V_s = V_{12}\left(1 - \frac{S1}{C}\right) \tag{1}$$

$$V_r = V_{34}\left(1 - \frac{S2}{C}\right) \tag{2}$$

where

V_s = the striking velocity of the projectile
V_{12} = the velocity at the midpoint between screens 1&2
S1 = the distance from midpoint between screens 1&2 and the target
C = correction constant, 52.4 m
V_r = the residual velocity after penetration
V_{34} = the velocity at the midpoint between screens 3&4
S2 = the distance from midpoint between screens 3&4 and the target.

A 0.05 mm thick aluminum witness plate was used to record complete penetrations. A complete penetration is defined as occurring "when the impacting projectile, or any fragment thereof, or any fragment of the test specimen perforates the witness plate, resulting in a crack or hole that permits the passage of light when a 60-watt, 110-volt bulb is placed proximate to the witness plate." (5) A catch box, layered with felt pads and DuPont Kevlar fabric, was used to stop the projectile.

Two different characteristic velocities, V_{50} and V_c, were calculated. V_{50}, the velocity at which 50 percent of the impacts result in complete penetration, was calculated from the arithmetic mean of the five highest partial and five lowest complete penetration impact velocities. A complete penetration is defined as an impact that causes a perforation of the witness plate. A partial penetration is defined as an impact that does not cause a perforation of the witness plate. V_c, the critical velocity for complete penetration, was calculated by fitting the following equations (7, 8)

$$V_r^2 = AV_s^2 - B \tag{3}$$

$$V_c^2 = \frac{B}{A} \tag{4}$$

$$V_r = (A(V_s^2 - V_c^2))^{1/2} \tag{5}$$

where

V_s = the striking velocity of the projectile
V_r = the residual velocity after penetration
V_c = the critical velocity for complete penetration
A = the slope of the line
B = the intercept

to all striking and residual velocities where striking velocity was greater than or equal to the lowest complete penetration velocity. A minimum of 20 shots was used for each set of samples, with at least eight shots spread over the range from V_{50} to approximately 120 m/s above the V_{50}.

RESULTS AND DISCUSSION

The ballistic testing results are summarized in *Table 1*. The ballistic testing results are not easily discernible. These materials have different compositions, number of layers, thicknesses, and areal densities. The failure mechanism is also important. It is unacceptable for the material to produce spall when impacted. Spall is the detachment or delamination of a layer of material in the area surrounding the location of impact, which may occur on either the front or rear surfaces of the sample and is produced as a result of a brittle failure mechanism.

Ballistic testing results are usually compared with regard to the material's areal density. This is the mass of the material per unit area or the density of the material multiplied by the thickness. To compensate for the various areal densities of the samples, the V_c and V_{50} values have been normalized to a 3 kg/m^2 areal density. This normalization is an acceptable treatment based on data in *Figs. 2* and *3* that demonstrate a relationship between V_c or V_{50} and areal density with the exception of two PC/SAN samples. Linear regressions for the V_c and V_{50} *vs.* areal density yield an average correlation coefficient of 0.951. Values for the 70/30 PC/SAN blend and 233 layer samples were not included in the regression, as it is clear in *Figs. 2* and *3* that those points are outlying values; however, values for two injection molded polycarbonate samples from a previous study were included (9) demonstrating the general applicability of the relationship. V_c and V_{50} values were normalized to a 3 kg/m^2 areal density by the following equation,

$$V_n = [a(\ln 3 - \ln D)] + V \quad (6)$$

where

V_n = the normalized V_c or V_{50} for the sample
V = V_c or V_{50} for the sample
D = the areal density in kg/m^2
a = the slope of the regressed line (0.8327 for V_c, 0.8017 for V_{50}).

A direct comparison between samples is now possible. The next variable to consider is the number of layers. Since the normalization effectively changes the dimensions of the sample, the number of layers is no longer a meaningful value; instead the average layer thickness is considered. A 3 mm thick sample with 3000 layers is not the same material as a 2 mm thick sample with 3000 layers but a 2 mm thick sample with an average layer thickness of 0.001 mm could be considered to be made of the same material. *Figures 4* and *5* show plots of the normalized V_c and V_{50} *vs.* the log of the average layer thickness. Most of the data fall between 155 and 200 m/s for both normalized V_c and V_{50}. The exception to this range are the 70/30 PC/SAN samples. Samples with eighty percent or more polycarbonate showed no effect of layering. There is a significant improvement in both the V_c and V_{50} in the 70/30 PC/SAN samples that occurs between the 233 and 929 layer samples. This improvement continues into the 1857 layer sample and is validated by the sixty percent PC/PCTG samples.

Figures 6 and *7* show plots of the normalized V_c and V_{50} *vs.* the percent composition of polycarbonate. For the PC/PCTG microlayer samples, the results were rather uniform. For the precision of the test method, the differences in the results may be statistically insignificant. The precision in the V_c is deter-

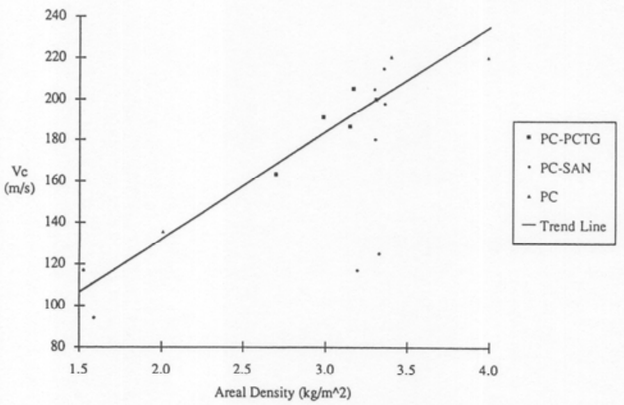

Fig. 2. V_c vs. areal density for microlayer sheets.

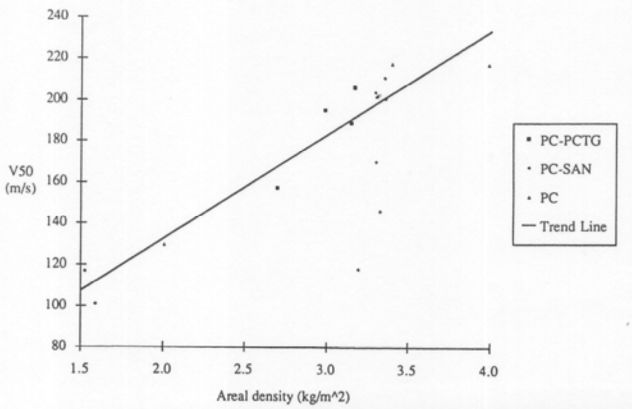

Fig. 3. V_{50} vs. areal density for microlayer sheets.

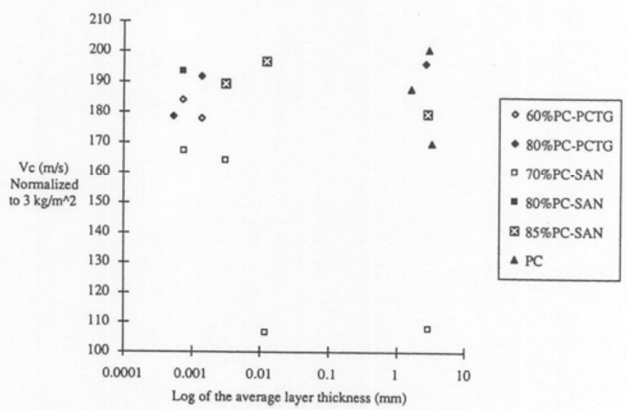

Fig. 4. V_c normalized to 3 kg/m^2 vs. log of the average layer thickness.

mined by the x-intercepts of a confidence band for the regression of each ballistic data set (10). A 95% confidence interval for the V_c is given as the ± associated with each V_c in *Table 1*. The precision in the V_{50} can be estimated by the range in each data set used for the calculation of V_{50}. This range is represented as the ± associated with each V_{50} in *Table 1*. The range is not a true ± since the calculated V_{50} need not be centrally located within the range.

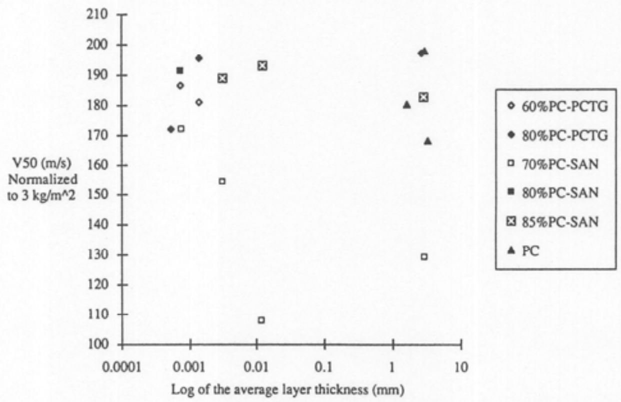

Fig. 5. V_{50} normalized to 3 kg/m² vs. log of the average layer thickness.

The results for the PC/SAN microlayer samples are very different. The 70/30 PC/SAN has a range of results from 108 to 172 m/s normalized V_{50} with a general trend of increasing normalized V_{50} with increasing number of layers. The 80/20 and 85/15 PC/SAN are less scattered. It appears that the V_c and V_{50} drop off with less than eighty percent polycarbonate in the PC/SAN composite. The highest normalized V_c and V_{50} values are 200 and 198 m/s for sample 25C, the extruded polycarbonate control sample.

The material behavior on impact and optical appearance are as important as the material performance. *Table 2* lists the optical appearance and fraction of brittle failures for the microlayer materials. The PC/SAN blends have 100 percent brittle failures, while the PC/PCTG blend and the polycarbonate sheet have no brittle failures. In both the PC/SAN and the PC/PCTG microlayer materials, the fraction of brittle failures decreases with both increasing polycarbonate composition and increasing number of layers.

The ballistic performance of the PC/SAN microlayer sheets conform to the impact results of Im *et al.* (3) for PC/SAN microlayer sheets at 3.4 m/s impact velocity. Im found that impact strength increases with polycarbonate content and also with the number of

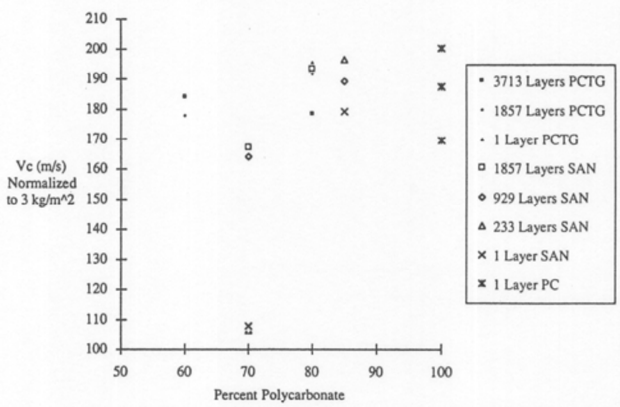

Fig. 6. V_c normalized to 3 kg/m² vs. percent composition of polycarbonate.

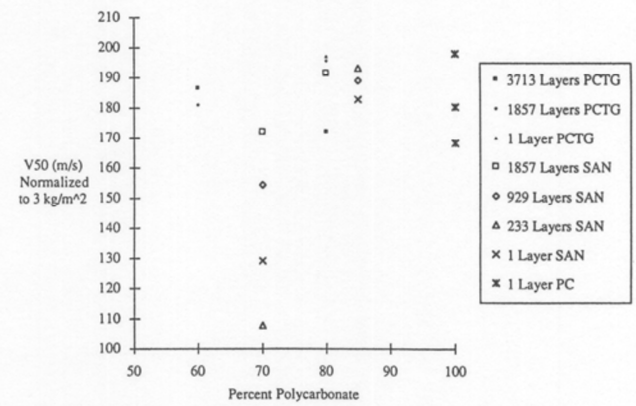

Fig. 7. V_{50} normalized to 3 kg/m² vs. percent composition of polycarbonate.

Table 2. Optical Appearance and Fraction of Brittle Failures for the Microlayer Materials.

Sample ID	% Composition Polycarbonate	Second Polymer	Number of Layers	Optical Appearance	Fraction of Brittle Failures	
25B	85	SAN	Blend (1)	opaque	24/24	(100%)
25A	70	SAN	Blend (1)	opaque	39/39	(100%)
15B	85	SAN	233	clear	5/20	(25%)
13B	70	SAN	233	clear	29/32	(91%)
19C	85	SAN	929	clear	7/24	(29%)
19B	70	SAN	929	clear	18/28	(64%)
41A	80	SAN	1857	clear	0/24	(0%)
39B	70	SAN	1857	clear	2/28	(7%)
55B	80	PCTG	Blend (1)	clear, lt. yellow	0/20	(0%)
49C	80	PCTG	1857	clear, lt. yellow	1/28	(4%)
49A	60	PCTG	1857	clear, lt. yellow	3/23	(13%)
55A	80	PCTG	3713	clear, lt. yellow	0/23	(0%)
53A	60	PCTG	3713	clear, lt. yellow	2/32	(6%)
25C	100		1	clear	0/24	(0%)

layers for a given polycarbonate content. The PC/SAN microlayer sheets showed a brittle to ductile transition corresponding to a sharp rise in the impact strength. This transition shifted to a lower polycarbonate content with increasing number of layers but shifted to a higher polycarbonate content when tested at higher strain rates. Im also reported that a 55/45 PC/SAN with 391 layers has 95 percent of the impact strength of the polycarbonate control.

The PC/SAN samples in this study, for the most part, contain a greater number of layers than the materials used in Im's standard impact study and this study's composition is predominately polycarbonate. Materials tested in this study would be within 95 percent of the impact strength of the polycarbonate control used in Im's impact study, except for the 233 layer PC/SAN sample. Thus, few clear trends for the normalized V_c and V_{50} ballistic impact results are noticeable. The precision of the ballistic test for V_c and V_{50} is not great enough to discern the slight differences in the impact strength of the materials. The ballistic performance of the PC/PCTG microlayer materials should also be able to be explained in a similar manner especially since PCTG, rather than SAN, is more like polycarbonate.

CONCLUSIONS

V_c and V_{50} follow linear relationships with areal density which allow the results to be normalized. Two trends can be seen for the normalized velocities. For the PC/SAN microlayer composite, the V_c and V_{50} decrease with less than eighty percent polycarbonate. In both the PC/PCTG and PC/SAN, the fraction of brittle failures decrease with both increasing polycarbonate composition and number of layers. The microlayer composites do show some promise as a ballistic armor material since some samples performed as well as and better than injection molded polycarbonate.

ACKNOWLEDGMENTS

The author would like to thank Mr. Jeffrey N. Bremmer and the Dow Chemical Corporation for supplying the extruded microlayer samples.

This paper reports research sponsored by the U.S. Army Natick Research, Development and Engineering Center and has been assigned TP-3378 in the series of papers approved for publication.

REFERENCES

1. W. J. Schrenk and T. A. Alfrey, Jr., in *Polymer Blends*, vol. 2, pp. 154–7, D. R. Paul and S. Newman, eds., Academic Press, Inc., New York (1978).
2. M. Ma, J. Im, A. Hiltner, and E. Baer, *J. Appl. Polym. Sci.*, **40**, 669 (1990).
3. J. Im, E. Baer, and A. Hiltner, in *High Performance Polymers*, p. 175, E. Baer and A. Moet, eds., Hanser Publishers, New York (1991).
4. E. Shin, A. Hiltner, and E. Baer, *J. Appl. Polym. Sci.*, **47**, 269 (1993).
5. Military Standard, MIL-STD-662E, "V_{50} Ballistic Test for Armor" (Jan. 22, 1987).
6. R. A. Muldoon, "Determination of Coefficient of Drag (K_D) and Development of Velocity Loss Equation for the Fragment-Simulating Type Projectiles Used to Evaluate Personnel Armor Material," *Watertown Arsenal Laboratory Report No. WAL 760/503* (Jan. 27, 1953).
7. R. F. Recht and T. W. Ipson, *J. Appl. Mech.*, Series E, **30**, 384 (1963).
8. J. P. Lambert and G. H. Jonas, "Towards Standardization in Terminal Ballistics Testing: Velocity Representation," *USA Ballistic Research Laboratory Report No. 1852* (January 1976).
9. W. G. Kohlman, "Mechanical Properties of Polycarbonate/Polysulfone and Polycarbonate/Polyetherimide Blends" (U), *USA Natick R, D&E Center Report No. NATICK/TR-91/025* (April 1991).
10. W. W. Daniel, *Biostatistics: A Foundation for Analysis in the Health Sciences*, 3rd Ed., p. 290, John Wiley & Sons, New York (1983).

Revision received March 1994