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Delamination Controlled Ballistic Resistance of Polyethylene/Polyethylene Composite Materials

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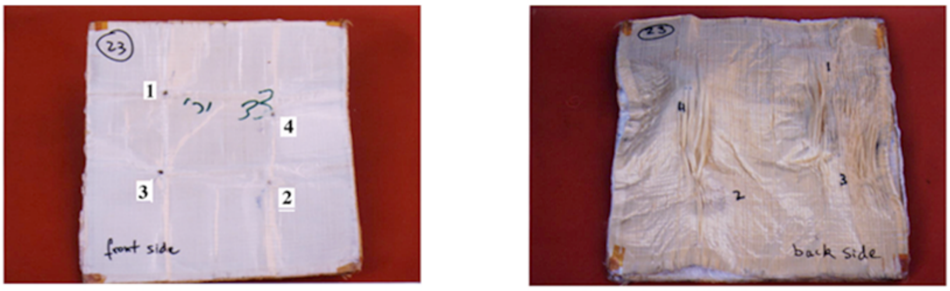
The ballistic response of polyethylene/polyethylene composites to impact by Uzi bullets was investigated. The plates exhibited an average ballistic resistance, V_{50}, of approximately 90 m/s per 1 kg/m^2 area density. In term of the protection level per thickness, the ballistic resistance was 76 m/s per 1 mm. Visual and microscopic examinations identified indentation and delamination as the prevailing failure mechanisms. The delamination energy calculated on the basis of a simple delamination model considering the fracture surface energy of the matrix was shown to balance fully the dissipated kinetic energy of the bullet, while the contribution of the fiber fracture process was negligible. That was taken as strong circumstantial evidence for the significant role of this failure process in the ballistic resistance of these composites.

Visual Examination

Fig. 1 presents two views of a PE/PE plate, showing 4 penetration holes in the front side and 4 bulges (indentations) in the back (the numbers on the plate mark the firing serial order). It is also noted that each indentation consists of a sequence of delaminations whose diameter and extent grow with the serial number of the bullet.



a b

Fig. 1 Front (a) and back (b) views of a composite plate.
The marked numbers designate the serial order of the bullets

The role of delamination can be studied by analyzing crushed bullets retrieved from between the delaminated laminae. Fig.2 presents a front view of the crushed bullets retrieved from a plate (the numbers mark the firing serial order), indicating a decreasing order of the crushed diameter. In fact, the diameter of the crushed bullet decreases linearly as a function of the serial number of the bullet. Also, it can be seen by comparing Fig. 1b with 3 that the diameter of the crushed bullet correlates well with the reciprocal diameter of the delamination and indentation associated with that bullet.

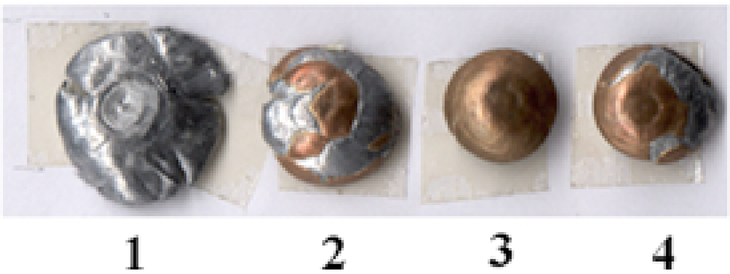


Fig. 2 A front view of the crushed bullets retrieved from the plate in Fig. 1
(the numbers mark the firing serial order)

Energy Calculation

Considering linear elastic fracture behavior of the PE fibers, the energy U_{fb}, associated in fiber breakage across a penetration hole of diameter y_{pen} is given by:

$$U_{fb} = \frac{N\sigma_{fu}^2 y_{pen} \pi r^2}{2E_f}$$

where σ_{fu} is the ultimate strength, r is the radius and E_f is Young's modulus of the fiber and N is the number of broken fibers. The fiber volume fraction is given by $\phi_f = N\pi r^2/ty_{pen}$, for a plate thickness t, hence

$$U_{fb} = \frac{\sigma_{fu}^2 y_{pen}^2 t \phi_f}{2E_f} \tag{1}$$

Assuming that the fracture surface energy of delamination is identical to γ_m, the fracture surface energy of the matrix (upper bound) and that y_{del} is the diameter of the delamination zone, then for n delamination planes the delamination energy U_{del} is given by:

$$U_{del} = \frac{n y_{del}^2 \pi \gamma_m}{2} \tag{2}$$

Taking $t = 5$ mm, $\phi_f = 0.72$, $\sigma_{fu} = 3.4$ GPa, $E_f = 105$ GPa, $n = 3$-5, $y_{del} = 40$-60 mm, $y_{pen} = 9$ mm (equal to the bullet diameter) and $\gamma_m = 40$ kJ/m^2 ($\gamma_m = G_c/2$, half the strain energy release rate), equations 1 and 2 produce: $U_{fb} = 16$ J and $U_{del} = 628$ J. Hence, the total calculated energy dissipated in the plate amounts to 644 J of which the contribution of the fiber breakage process is negligible compared with that of delamination. The most striking result is that this calculated energy is almost identical to the kinetic energy of the bullet (608 J) for $V_{50} = 390$ m/s. The good agreement between the prediction of the delamination model and the value of the dissipated kinetic energy is taken as strong circumstantial evidence for the significant role of this failure process. However, this argument is not sufficiently conclusive to exclude with reasonable certainty other potentially significant mechanisms such as indentation.