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BALLISTIC PERFORATION OF POLYCARBONATE SHEET AND ITS HIGH STRAIN RATE RESPONSE

N.A. FLECK, S.C. WRIGHT, J.H. LIU and W.J. STRONGE

Department of Engineering, University of Cambridge, Trumpington Street, GB-Cambridge CB2 1PZ, Great-Britain

Résumé : Les propriétés balistiques de feuilles de polycarbonate sont étudiées à l’aide d’impacts de projectiles cylindriques aux vitesses comprises entre 100 et 600 m/s. La pénétration se réalise par expansion plastique axissymétrique, avec fissurations multiples en cône sur la face avant du projectile. Les propriétés en cisaillement à haute vitesse de déformation sont mesurées et comparées à celles du PMMA.

Abstract - The ballistic response of polycarbonate sheets is examined using cylindrical projectiles at impact speeds in the range 100 ms⁻¹ to 600 ms⁻¹. Penetration is by axisymmetric plastic expansion, with multiple cone cracking at the leading edge of the projectile. High strain rate properties in shear are reported, and compared with those for PMMA.

1 - BALLISTIC TESTS

Steel cylinders of length, \( l = 9 \) mm and diameter, \( d = 7 \) mm were fired from a gas gun at a velocity \( V \) in the range 100 ms⁻¹ to 600 ms⁻¹. The targets were made from Makralon Type 281 polycarbonate sheets of diameter 102 mm and thickness 2, 5 and 12 mm. The critical velocity for perforation increases with sheet thickness, Fig. 1;

![Fig. 1: Plot of critical speed for perforation of PC plate by a 7 mm diameter x 9 mm long flat-nosed cylinder, as a function of plate thickness, h.](http://dx.doi.org/10.1051/jphyscol:1988322)
penetration is by axisymmetric plastic expansion coupled with local cracking at the periphery of the flat-nosed cylindrical projectile. Cracking occurs by the formation of conical cracks ahead of the projectile in the following sequence. A conical crack nucleates at the front edge of the projectile and later arrests at a length of about 2 mm; crack arrest is due to the rapid decrease in stress intensity factor with crack extension. The projectile moves forward and a new conical crack forms. Evidence for this mechanism is provided by high speed photographs of the perforation process, taken through the edge of the transparent target; quasi-static indentation tests produced a similar cracking sequence and similar fracture surfaces. The extent of plastic deformation in the target is easily seen after the ballistic test since the refracture index of the polycarbonate changes with plastic deformation, see Fig. 2.

The kinetic energy required for perforation by the 9 mm length × 7 mm dia. cylinder is compared with that for a 7 mm diameter ball in Fig. 3. Results are plotted in

![Fig. 2: View of hole and plastic zone through side of 12 mm thick PC plate, after impact. Projectile motion is from top to bottom.](image1)

![Fig. 3: Comparison of kinetic energy required to perforate PC plate by a steel cylinder and by a steel ball.](image2)
the form of kinetic energy/($a_y \times$ cross sectional area of projectile $\times$ sheet thickness) versus (sheet thickness)/(projectile diameter). The compressive yield stress $a_y$ is given the value $a_y = 100$ MPa, from the results of Walley et al. [1].

It is apparent that greater kinetic energy is required for perforation by the slug than by the ball. This is consistent with the argument that more redundant plastic work is done for flow past the sharp corner of the cylinder, compared with flow past the more streamlined ball.

2 - HIGH STRAIN RATE TESTS

During ballistic impact, the PC undergoes shear yielding with no evidence of crazing. High strain rate torsion tests were performed in order to determine the deformation and fracture response of the PC. A split Hopkinson torsion bar was used to determine the true shear stress $\tau$ versus shear strain $\gamma$ response, at strain rates in the range $\dot{\gamma} = 500$ s$^{-1}$ to 2000 s$^{-1}$ and temperature $T$ in the range 20°C to 200°C. Tubular specimens of gauge length 4 mm, outer diameter 17 mm and wall thickness 0.5 mm were used. The stress-strain response was deduced from stress wave measurements on the input and output bars using strain gauges and a storage oscilloscope.

The $\tau - \gamma$ response for temperatures in the range $T = -100^\circ$C to 200°C and $\dot{\gamma}$ in the range 500 s$^{-1}$ to 2000 s$^{-1}$ typically consists of four stages, Fig. 4,

1. An initial visco-elastic response until an upper yield point is reached at $\gamma = 0.1 - 0.2$.
2. Strain softening occurs and the stress drops to a constant lower yield value, $\tau_L$, until $\gamma \approx 1$.
3. The specimen strain hardens at an approximately linear rate with strain, until
4. the specimen fractures at $\gamma \approx 1.5 - 2.0$, apparently by adiabatic shear localisation.

The Eyring theory of viscous flow may be used successfully to model the influence of strain rate and temperature on the upper or lower yield stress. In multi-axial form, the Eyring equation may be written

\[ Y = \tan \phi' \]

Fig. 4: Typical $\tau - \gamma$ response of PC in simple shear.
\[
\frac{-c}{\dot{\varepsilon}/\dot{\varepsilon}_o} = \exp\left[-(q/kT)(1 - \frac{\sigma}{\sigma_o} - \frac{\sigma_m}{\sigma_o})\right]
\]

where $\sigma$ is the von Mises effective Cauchy stress, $\sigma_m$ is the mean hydrostatic stress, $\dot{\varepsilon}$ is the effective Eulerian strain rate, $\dot{\varepsilon}_o$, $\sigma_o$ and $\sigma_m$ are material constants, $q$ is the thermal activation energy and $k$ is Boltzmann's constant. The Eyring equation predicts a linear relationship between $\gamma y/T$ and $\ln \dot{\gamma}$. This is observed for PC, see Fig. 5. At temperatures below 20°C, the constants in the Eyring equation must change in order to fit the data. This suggests that a different yield mechanism operates at low temperatures.

![Fig. 5: Plot of (lower yield stress, $\gamma y$)/(absolute temperature, T) against $\ln \dot{\gamma}$, for PC in simple shear.](image)

There is evidence that final fracture may be due to adiabatic shear localisation. A perturbation analysis suggests that localisation starts when,

\[
\tau = \rho C_p \frac{\partial T}{\partial \gamma}
\]

where the shear stress $\tau$ depends primarily on $\gamma$ and $T$ (and is assumed independent of $\dot{\gamma}$), $\rho$ is the density and $C_p$ is the specific heat capacity. Assuming adiabatic conditions (so that $\tau \dot{\gamma} = \rho C_p \partial T/\partial \gamma$), localisation is triggered when

\[
\frac{\partial \tau}{\partial \gamma} + \frac{\partial \tau}{\partial T} \frac{\partial T}{\partial \rho C_p} = 0
\]

This simple theory predicts a shear ductility $\gamma$ of about 2.0 for the high rate tests at $T = 20^\circ C$, $100^\circ C$ and $150^\circ C$. The observed ductility is about 1.8 for these temperatures: the hypothesis of fracture due to adiabatic shear localisation finds support. Examination of the fracture surfaces in the scanning electron microscope shows extensive plastic shear deformation rather than brittle fracture, Fig. 6. Again, the evidence points towards adiabatic shear localisation as the fracture mechanism.
Fig. 6: (a) Low magnification, and (b) high magnification views of the fracture surface of a PC specimen in simple shear. $T = 20^\circ C$, $\dot{\gamma} = 2000 \text{ s}^{-1}$. The arrow lies on the fracture surface and points in the shear direction, in each micrograph.

3 - CONCLUSIONS

Polycarbonate behaves in a similar manner to metals in its ability to withstand ballistic impact, although the detailed mechanism of perforation is somewhat different. The high strain rate response of PC also resembles that of metals; it undergoes shear yield, displays strain hardening and then fractures possibly by adiabatic shear localisation.

REFERENCES