Uniaxial Compression and Combined Compression-and-Shear Response of Amorphous Polycarbonate at High Loading Rates

Vikas Prakash, Namit Mehta
Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Glennan 616B, Cleveland, Ohio 44106-7222

We present results of a study conducted to better understand the yield and flow response of amorphous poly(bisphenol A carbonate), PC-Lexan® (PC), under uniaxial compression and combined compression-and-shear impact loading. A split Hopkinson pressure bar (SHPB) is utilized to obtain nearly adiabatic uniaxial compression response of the PC in the strain-rate range of 1000–2000 s⁻¹. Since temperature is expected to play an important role in governing the dynamic response of PC, nearly isothermal SHPB tests are also conducted and compared with the adiabatic response. In order to investigate the coupling of shear behavior and dilatation in PC at high loading rates, combined compression-and-shear plate impact experiments are conducted at strain-rates in the range of 10⁵–10⁶ s⁻¹. In addition, novel plate impact experiments are conducted to better understand the evolution of the shear resistance of PC in response to sudden alterations (drop) in hydrostatic pressure under extremely high shearing rates. POLYM. ENG. SCI., 52:1217–1231, 2012. © 2011 Society of Plastics Engineers

INTRODUCTION

The last century has witnessed a tremendous increase in the use of polymers as engineering materials. Based on that experience, it is anticipated that polymers will play a continuously growing role. Although used widely in virtually all engineering fields, their nonlinear dynamic behavior with respect to time dependent responses is not well understood. This lack of knowledge is particularly disturbing in view of the current design protocols for polymeric components that are subject to impact loading environments. Specifically, there exists very little understanding of polymers that parallels our description of plastically deforming solids. To achieve reliable and efficient material design, it is, thus, important to continue to investigate the dynamic behavior of polymers.

The present investigation focuses on a typical engineering polymer, PC-Lexan®, manufactured by General Electric. PC-Lexan® is a transparent, amorphous thermoplastic poly-condensate, possessing excellent strength and toughness. The molecular structure of poly(bisphenol A carbonate) constrains the mobility of individual molecules, resulting in good thermal resistance and a high viscosity. One of the most attractive features of PC-Lexan® is its high specific impact strength (9.0 J cm⁻¹), when compared to acrylonitrile butadiene styrene (ABS) (4.1 J cm⁻¹), polyvinyl chloride (PVC) (3.2 J cm⁻¹), and Nylon 6/6 (1.9 J cm⁻¹). This makes it a prime candidate for use in military applications where the strength-to-weight ratio is of primary concern, e.g., lightweight body armor including transparent shields for military purposes. Besides being useful to the military, today, PC-Lexan® is being used in many day-to-day civilian applications, such as impact resistant compact-disc covers, exterior automotive components, medical supply components, plastic lenses for eyeglasses, to name a few.

In this article, we present results of an experimental study conducted to better understand the yield and flow behavior of PC in its glassy state under high-strain-rate uniaxial compression and ultra-high-strain-rate combined compression-and-shear loading. Amorphous PC was chosen for the investigation because its amorphous character avoids interactions between the different phases, as in crystalline polymers. Further motivation for this choice was provided by the relatively wide use of PC as an engineering material, and data acquired on its properties might also improve our understanding of the yield and flow response of amorphous polycarbonate as a function of strain, strain-rate, temperature, and hydrostatic pressure. The quasi-static response of PC is investigated by using a servo-hydraulic test machine at strain rates in the range of 0.001–0.002 s⁻¹. Using the split Hopkinson pressure-bar (SHPB) nearly adiabatic compression tests are conducted in the intermediate strain-rate regime ranging from 1000 s⁻¹ to 2000 s⁻¹. Since temperature is understood to play...
an important role in governing the dynamic response of polymers, nearly isothermal tests are also conducted by employing incremental compression tests in the SHPB. Moreover, in order to investigate the behavior of PC at strain rates in the range of $10^5$–$10^6$ s$^{-1}$, high-strain-rate combined compression-and-shear plate impact experiments are employed. In these experiments, thin films of PC are sandwiched between two hard elastic plates and impacted by an elastic flyer plate in a pressure-shear configuration. Moreover, by employing a suitable combination of front and the rear target plates, a sudden change (drop) in normal stress is induced during the high-strain-rate shearing process. This results in a sudden drop in the applied normal stress (and hydrostatic pressure), thus allowing the investigation of the coupling between volumetric and equi-voluminal (shear) deformations in glassy polymers.

The motivation for the combined compression-and-shear plate-impact experiments stems from the fact that in classical metal plasticity based on dislocation mechanisms, the volumetric and shear behaviors are typically considered uncoupled: the classical plasticity theory addresses shear only, and the von Mises criterion leads to a convenient unifying constitutive description that is independent of the deformation rates in terms of the octahedral shear stress. Even in the elegantly developed theory of linear viscoelasticity [1–3], the volumetric and shear behaviors are considered to be uncoupled. However, when polymers experience strains on the order of a percent or more, nonlinear viscoelasticity starts to make marked contributions [4]. Knauss and Emri [5, 6] have observed experimentally that the shear behavior of polymers is clearly influenced by dilatation. On the other hand, as a complement of that observation, shear stress may also produce volumetric change in polymers [7–18]. Thus, it stands to reason that even under shear loading some volume-dependent influence exists. The well-established explanation for this phenomenon is based on the free-volume content of a polymer—the less the available free volume the harder it is for the chains to move. Therefore, one can associate the lower free volume (due to high pressures) to the greater constraint on the thermally activated chain motion. Consequently, besides the traditional uniaxial laboratory experiments, experiments on specimens subjected to multi-axial stresses are necessary to begin understanding how to characterize the corresponding time-dependent behavior of polymers.

**EXPERIMENTAL PROCEDURE AND RESULTS**

The specimens for the quasi-static and the high-strain-rate SHPB compression tests were all of right cylinder circular geometry, with a diameter of approximately 11.13 mm and 5.8 mm in height, and were machined from amorphous polycarbonate rods of $\sim$12.5 mm in diameter. Specimens with a length to diameter ratio of 0.5 were used so as to prevent barreling of the specimens due to effects of interfacial friction between the specimen and the loading platens [19, 20]. Also, a length-to-diameter ratio of 1:2 has been shown to be optimal in negating the effects of radial and longitudinal inertia in the specimen plates [21]. Special care was taken during machining the specimens so as to minimize the residual stresses in the specimen. In this regards, after machining the specimens were stress relieved by following an annealing process, during which the temperature of the machined specimens was increased to 150 $^\circ$C and held at that level for 2 h, followed by cooling to room temperature at a cooling rate of 10–15 $^\circ$C h$^{-1}$. It is to be noted that the glass transition temperature of polycarbonate is 144 $^\circ$C, which is lower than the temperature used in the annealing process. At the end of the cooling cycle, the specimens were assumed to be essentially in an equilibrium state and free of residual stress derived from any previous deformation history (processing or machining). The ends of the specimens were then lightly hand polished to make them smooth, ensuring minimal friction between specimen and the compression plates. In all experiments, a dynamic equilibrium condition was assumed to have been attained in the specimens before yielding, due to the short specimen lengths employed in the tests.

**Quasi-Static Compression Tests**

The quasi-static experiments were conducted on a Schenck Pegasus servo-hydraulic machine. The machine is capable of delivering 100 kN of force in compression or tension, and uses a Schenck Pegasus Digital 5900 series servo-controller for accurate actuator response. The controller has an active feedback loop system to monitor and maintain a constant engineering strain rate deformation within the specimen. A linear variable differential transformer (LVDT) mounted on the side rack measures the movement and position of the gripping jaws, resolving motion up to 250 $\mu$m. Molybdenum grease was applied liberally on the top and bottom plate surfaces to ensure minimal friction at the specimen–plate interface. Figure 1 shows the true-stress true-strain behavior of PC in uniaxial compression obtained from tests carried out at true strain rates of 0.011 s$^{-1}$ and 0.0187 s$^{-1}$. At the two strain-rates, PC shows three characteristic phases during the deformation process. During the initial loading phase (Region O–A), the material exhibits nonlinear viscoelastic response; at very small strains (<0.025) the material behavior is nearly linear elastic. The elastic region is the result of intermolecular interactions between chains (van der Waal forces), where the chain segments partially and reversibly rotate and/or translate with respect to one another. As the stress level increases, more localized deformation regions develop within the bulk material where the stress is large enough to overcome the secondary intermolecular forces, and the chains rotate and/or slide to a new position. At this point the response becomes markedly non-linear, and the slope of the stress–strain curve decreases. Eventually, enough localized events occur and
percolate through the material such that the entire material yields and flows plastically without any further increase in stress. This local maximum in the stress–strain curve is recognized as the polymer’s yield point. Moreover, in the strain rate range 0.011–0.0187 s\(^{-1}\) the yield strength of the PC is nearly independent of the applied strain rate. The second phase (Region A–B) is associated with yield and early part of the post-yield behavior. During this phase an increase in strain results in a strain softening, whereby the stress needed to further deform the polymer decreases. The strain softening indicates that the intramolecular barriers to chain segment rotation decrease with plastic strain, thus making local chain-segment rotations to occur at lower levels of stress. As plastic deformation increases, the network structure evolves with chain segment rotations from an initial isotropic random configuration to an oriented network with molecular chains preferentially aligned with the direction(s) of maximum stretch. In a compression test, this corresponds to an equibiaxial alignment of chains in a plane perpendicular to the compression axis. With increased plastic straining, the structure deviates further and further away from its natural disordered state leading to a decrease in the overall entropy of the polymer. It is this entropic change—most significant once the molecular chains are stretched and their alignment begins to approach their extension limit in the maximum stretch direction—that causes the observed strain hardening in the region beyond Point B in Fig. 1 (strains in excess of \(\sim 25–30\%\)).

Dynamic Uniaxial Compression Tests

In order to understand the dynamic compressive behavior of PC at strain-rates in the range 100–2000 s\(^{-1}\), cylindrical PC tabs were impacted using a SHPB. Since during a typical high-strain-rate deformation test the time available for conduction of heat is short, a rapid temperature build-up is expected within the specimen. This condition and its effects are expected to be more pronounced in the case of polymers, especially in view of their relatively low thermal conductivity and low glass-transition temperatures. In view of this, in the present study, along with nearly adiabatic tests nearly isothermal SHPB tests are also designed and conducted by deforming the specimens in a series of incremental steps at strain-rates similar to those used in the adiabatic compression tests. Comparison of the material response obtained from the adiabatic and isothermal tests can then be used to provide critical information on thermal softening during dynamic compression of the amorphous PC.

Nearly Adiabatic SHPB Dynamic Compression Tests

A SHPB is employed to conduct the dynamic compression tests at strain rates in the range 100–2000 s\(^{-1}\). Details of the SHPB technique can be found elsewhere [22, 23]. The schematic of the SPHB facility at CWRU is shown in Fig. 2. The incident and transmitter bars are 19.05 mm in diameter and are made from maraging steel with nominal yield strength of approximately 2500 MPa. The striker bar is approximately 0.61 m (2 feet) in length, while the incident and transmitted bars are approximately 1.5 m (5 feet) long. The 0.61 m length of the striker bar allows a pulse width of approximately 250 \(\mu\)s during the
A pair of strain gages (measurement group WK-06-250BF-10C) is strategically attached on the incident and transmitted bars. The strain gages are used in combination with a Wheatstone bridge circuit, a differential amplifier (Tektronix 5A22N), and a digital oscilloscope (Tektronix TDS 420) to record the incident, transmitted, and the reflected strain pulses during the test. Due to the long length of the incident and the transmitter bars, anti-frictional roller bearings are placed intermittently along the length to align and provide support to the bars. The striker bar moves freely on two anti-frictional Teflon bearings in the gun barrel. The gun barrel is attached to a pressurizing chamber storing high-pressure air, which when released, propels the striker bar. The specimens used in the tests were 11.2 mm in diameter and about 5.6 mm in height. As in the case of the quasi-static experiments, specimens with an $L/d$ ratio of 0.5 are used along with hand polishing of the specimen ends to prevent barreling of the specimens during large plastic deformation. Moreover, molybdenum grease is applied at the contacting surfaces to reduce the effects of friction to minimal levels.

Typical SHPB results for PC under adiabatic compression are presented in Fig. 3. For the sake of comparison, results of two quasi-static strain rate experiments are also shown in the figure. The stress–strain behavior is observed to be strongly dependent on the applied strain rate. As the strain rate is increased, both the initial elastic moduli as well as the yield stress are observed to increase. Moreover, at the elevated strain rates, the flow stress, at all levels of plastic strain, are observed to be much higher than the stress measured at the quasi-static loading rates. The three phases observed during quasi-static deformation, i.e., the initial linear elasticity and the nonlinear viscoelastic response up to yield, strain softening, and subsequent work hardening, are also carried over to the higher strain rates. The critical strain at which work hardening overtakes the strain softening behavior remains at approximately 0.25, indicating that the critical strain level is nearly independent of the applied strain rate. It is important to note that the sudden drop in flow stress at the end of each stress–strain curve does not indicate material softening, but rather is a consequence of the end of the compression pulse. The homogeneous nature of the deformation was confirmed via post-mortem analysis of the specimens with little or no barreling being observed in the post-test specimens.

Figure 4 is a summary of the yield strength levels obtained from the tests conducted in the present study. Within the low to moderate strain rate regime, the yield stress is found to increase linearly with the logarithm of strain rate, indicating that the yield behavior in this regime could be accurately explained in terms of a single activated process. At higher strain rates, the data reveal a distinct transition in the rate-dependent yield behavior of PC at a strain rate of $\sim 100 \text{ s}^{-1}$. The yield strength increases nearly linearly with the logarithm of strain rate; however, the slope of the line is much greater in this high strain rate regime. The data are in agreement with the work of Bauwens et al. [24], and Walley and Field [25], among others. Moy et al. [26] also conducted uniaxial compression tests on PC at room temperature over the strain rate range $10^{-2}$–$10^{1} \text{ s}^{-1}$. They reported a transition in behavior to a regime of increased strain rate sensitivity at a strain rate of about $300 \text{ s}^{-1}$.

Based on previous work [24, 27, 28], the yield behavior transition can be linked to the well-documented $\beta$-processes in PC, which provide enhanced intermolecular resistance by restricting the rotations of the main-chain phenyl group. At elevated test temperatures and low strain-rates, the $\beta$-processes in PC are fairly compliant,
TABLE 1. Summary of the high-strain-rate SHPB tests conducted on PC in the present investigation.

<table>
<thead>
<tr>
<th>Shot no.</th>
<th>$\sigma_{\text{bar}}$ (MPa)</th>
<th>$v_0$ (m s$^{-1}$)</th>
<th>$\dot{\varepsilon}_{\text{avg}}$ (s$^{-1}$)</th>
<th>$\Delta T$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NXM9-10</td>
<td>263.1</td>
<td>13.6</td>
<td>1250</td>
<td>17</td>
</tr>
<tr>
<td>NXM1-2</td>
<td>315.7</td>
<td>16.4</td>
<td>1361</td>
<td>25</td>
</tr>
<tr>
<td>NXM3-4</td>
<td>336.8</td>
<td>17.5</td>
<td>1646</td>
<td>27.5</td>
</tr>
<tr>
<td>NXM11-12</td>
<td>378.9</td>
<td>19.6</td>
<td>1826</td>
<td>30</td>
</tr>
<tr>
<td>NXM7-8</td>
<td>389.4</td>
<td>20.2</td>
<td>1911</td>
<td>32.5</td>
</tr>
</tbody>
</table>

and most of the intermolecular resistance is associated with the rotations ($\alpha$-process) of the polymer main-chain segments; however, at low temperatures and/or high strain-rates, the $\beta$-processes become increasingly restricted, leading to significant levels of intermolecular resistance, and hence an increase in flow stress.

**Nearly Isothermal SHPB Dynamic Compression Tests**

A summary of the dynamic compression tests is presented in Table 1. The table shows the stress generated in the bar $\sigma_{\text{bar}}$, the velocity of the striker bar $v_0$, average strain rate in the sample $\dot{\varepsilon}_{\text{avg}}$, and an estimate of the temperature rise in the sample. The temperature rise was estimated based on the assumption that the deformation occurring in the PC is adiabatic, and 100% of the plastic work (area under the true-stress true strain curve) is converted to heat, i.e.

$$\Delta T(t) = \frac{\eta}{\rho c_p} \int_0^t \sigma \dot{\varepsilon} \, dt$$  \hspace{1cm} (1)

In Eq. 1, $\rho$ and $c_p$ are the mass density and specific heat capacity at constant pressure of PC, respectively, and $\eta$ is the fraction of plastic work converted to heat.

Using Eq. 1, the maximum temperature rise within the specimens is estimated to be 32 K, and occurs for Shot NMM7-8 at a strain rate of 1911 s$^{-1}$. Recent experiments by Rittel [29] and Lerch et al. [30] on PC have also indicated a temperature rise in a polymer disk under high-rate compression ($\sim 10^4$ s$^{-1}$) to be $\sim 40$ K with 80% plastic strain. However, in other polymers, such as, PMMA, even at strain rates as low as $10^{-1}$ s$^{-1}$, Arruda et al. [31] have measured a 20 K rise in temperature under large strain compression. At higher strain rates, the temperature increase in PMMA is expected to be even larger, and is expected to result in significant thermal softening.

In order to better understand the effects of heat generation during dynamic plastic deformation in PC, dynamic SHPB isothermal compression tests were designed and conducted at essentially the same strain rates as the adiabatic tests described above. The isothermal tests were conducted by incrementally deforming the specimens in a series of three deformation steps. To conduct the incremental tests, rings of pre-determined thickness were machined from high-strength 4340VAR steel and positioned on the face of the transmitter bar (shown schematically in Fig. 5). The outside diameter of these rings was about 19.1 mm while the inside diameter was 13 mm. The thickness of the rings was calculated based on the level of strain to which the PC specimens were to be incrementally deformed in each deformation step. Next, the PC specimen (approximately 11.13 mm in diameter), is placed at the center of the ring, and the incident and transmitter bars are brought gently into contact with the specimen. At impact, the compressive loading pulse deforms the specimen up-to the point when the incident bar comes in contact with the stopper ring. Note that the stopper rings limit the axial strain in the specimen such that the radial strains remain small and the outer surface of the deformed PC specimen does not come in contact with the inner diameter of the stopper rings. Also, after each deformation step, care is taken to allow sufficient time for heat dissipation. As a result the strain induced in the specimen in each step is well controlled. By using successively thinner rings the specimen is deformed under essentially isothermal conditions to the desired final level of strain.

Figure 6 compares the dynamic flow behavior of PC under isothermal and adiabatic test conditions. The solid lines trace the isothermal response while the dashed line represents the adiabatic response. The variance in strain rates between the isothermal and the adiabatic tests is approximately 1.2%. It is interesting to note that the dynamic flow behavior under both isothermal and adiabatic conditions is quite similar, so much so that the adiabatic and isothermal tests at the strain-rate of 1750 s$^{-1}$ almost overlap each other. As shown in Table 2, the maximum temperature rise estimated for the isothermal tests range from 6 K to 10 K. These increments in temperature are much smaller (almost one-third) when compared with
the temperature rise estimated for nearly adiabatic deformation.

The nearly similar behavior of PC under adiabatic and isothermal deformation conditions suggests that the effect of temperature rise due to plastic work under adiabatic conditions does not have a significant effect on the flow behavior of PC. It also suggests that perhaps the mechanism responsible for the conversion of plastic work to heat, i.e., energy dissipation, during dynamic deformation of PC is significantly different from other polymers, such as, poly(methyl methacrylate) (PMMA), and the actual temperature rise may be much smaller than that predicted by Eq. 1. Using direct measurements of temperature rise during dynamic deformation of PC, Bjerke [32] and Li [33] estimated the parameter $\eta$ for PC to be in the range of 0.5–0.6 during high rate compression. This is in contrast to the value of $\eta$ published in the literature for metals [29, 34–36], which is in the range of 0.8–0.95. Using $\eta = 0.5$, reduces the temperature rise during dynamic compression in PC; nevertheless, the measured temperature rise in PC indicates that PC does in fact heat up significantly under thermo-mechanically coupled adiabatic conditions. However, the associated changes in the dynamic stress versus strain behavior due to temperature rise in the PC at low to moderate strain rates are minimal because of the relative lack of temperature sensitivity of the storage modulus in the $\alpha$-regime, as measured by the dynamic mechanical analysis (DMA) from 0°C to 25°C (the storage modulus of PC only decreases by 3% [37]), and due to restrictions of the $\beta$-motion at the high strain-rates.

### High Strain Rate Plate-Impact Combined Compression-and-Shear Experiments

An 82.5 mm (3.25") bore single-stage gas gun at Case Western Reserve University was used to conduct the ultra-high-rate combined-compression-and-shear plate impact experiments. The schematic of the experimental configuration is shown in Fig. 7. The experiments involve the impact of a thick flyer plate mounted on a projectile with a stationary target plate. The target comprises a front and a back plate with a thin specimen sandwiched in between. Impact takes place at an angle $\theta$ relative to the direction of approach. The impacting flyer and target plates are ground and lapped flat, and are aligned parallel to each other prior to impact.

Upon impact, both longitudinal and shear waves are generated within the flyer and target plates. This leads to a high-strain-rate combined compression-and-shear loading of the sandwiched specimen. In all experiments conducted in the present study, the projectile velocity and the skew angle are controlled such that the flyer and target plates remain essentially elastic during impact. During the experiment, the time history of both the normal and transverse components of the particle velocity at the rear surface of the target-plate is measured by using non-contact laser-based diagnostics. The measurements of particle velocity are restricted to the time interval prior to the arrival of the unloading waves from the lateral boundary of the specimen. In view of this, during the
time interval of interest, the flyer and the target plates can be considered to be essentially infinite in their spatial dimension and the configuration be modeled as a semi-infinite half plane impacting on another. This simplification in test geometry along with the control of projectile velocity allows one-dimensional elastic wave theory to be used in obtaining the normal and shear stresses within the specimen.

In order to conduct the experiments, a flyer plate attached to a fiberglass projectile is accelerated down the gun barrel by means of compressed air. The rear end of the projectile has sealing O-Ring and a key that slides in the slotted keyway to prevent rotation of the projectile during its acceleration. Impact takes place in a target chamber evacuated to approximately 50 μm Hg. The vacuum helps to eliminate the air cushion between the flyer and the front target plate at the time of impact. This is essential since the presence of air cushion in between the flyer and the target plates can introduce, (a) a finite rise time in the stress pulse generated during impact, and (b) may cause slip at the flyer-target plate interface during the pressure-shear impact loading. To ensure the generation of plane waves with wave-fronts sufficiently parallel to the impact plates, the flyer and the target assembly are carefully aligned so that they are parallel to within 2°.

The target assembly used in the present investigation consists of a thin front plate and a relatively thicker rear plate, with the PC specimen sandwiched in between the two plates. The target assembly is then compressed gently with help of a special vice and is sealed using HARDMAN non-shrinking adhesive. Specially machined plastic rings, the target assembly is mounted on to a target holder. Two different front and rear target plate material combinations are utilized in the present experiments. In the first configuration, the flyer as well as the front and rear target plates are all machined from a high strength 7075-T6 aluminum alloy. This configuration is well suited for determining the dynamic shearing response of the polymer specimen at a known (pre-determined) hydrostatic pressure and shearing rate. In the second configuration, the flyer and the front target plates are machined from a 7075-T6-aluminum alloy, while the rear target plate is machined from Carpenter Hampden tool steel. The physical properties for 7075-T6 Al alloy and the CH tool steel plates are shown in Table 3.

For the constant hydrostatic pressure and the pressure-drop experiments, the flyer is approximately 76 mm in

| Table 3. Physical properties for 7075-T6 Al alloy and the CH tool steel plates. |
|-----------------------------------------------|-------|-------|
| Physical properties                         | 7075-T6 | CH    |
| Longitudinal wave speed, \(C_L\) (mm/μs)    | 6.23   | 5.98  |
| Transverse wave speed, \(C_S\) (mm/μs)      | 3.100  | 3.264 |
| Longitudinal impedance, \(\rho C_L\) (GPa/mm/μs) | 17.44   | 45.50 |
| Shear impedance, \(\rho C_S\) (GPa/mm/μs)   | 8.68   | 24.90 |
| Mass density, \(\rho\) (kg/m³)              | 2800   | 7612  |
| Young’s modulus, \(E\) (GPa)                | 71     | 207   |
| Shear modulus, \(\mu\) (GPa)                | 26.9   | 81.1  |
| Tensile strength, \(\sigma_{yield}\) (MPa)  | 572    | 2758  |

The interferometry signals are detected by NEWPORT silicon pin detector (Model 818-BB-21) having a rise time of less than 1 ns. The output of the photo detectors are amplified by suitable bandwidth digital amplifiers before they are fed to high sampling rate and high bandwidth oscilloscopes. The interferometer fringe record is analyzed to obtain the history of the normal and transverse particle velocities at the rear surface of the target plate.

**Flyer and Target Materials**

The target assembly used in the present investigation consists of a thin front plate and a relatively thicker rear plate, with the PC specimen sandwiched in between the two plates. The target assembly is then compressed gently with help of a special vice and is sealed using HARDMAN non-shrinking adhesive. Specially machined plastic rings, the target assembly is mounted on to a target holder. Two different front and rear target plate material combinations are utilized in the present experiments. In the first configuration, the flyer as well as the front and rear target plates are all machined from a high strength 7075-T6 aluminum alloy. This configuration is well suited for determining the dynamic shearing response of the polymer specimen at a known (pre-determined) hydrostatic pressure and shearing rate. In the second configuration, the flyer and the front target plates are machined from a 7075-T6-aluminum alloy, while the rear target plate is machined from Carpenter Hampden tool steel. The physical properties for 7075-T6 Al alloy and the CH tool steel plates are shown in Table 3. By utilizing a higher impedance material (CH tool steel) for the rear plate, a sudden drop in hydrostatic pressure can be introduced at the specimen plane. Such sudden alterations in hydrostatic pressures are important for the determination of effects of pressure on the shearing response of amorphous polymers.

For the constant hydrostatic pressure and the pressure-drop experiments, the flyer is approximately 76 mm in...
diameter and 13 mm in thickness. Also, the front and the rear target plates are 76 mm in diameter. For the constant pressure experiments, the thicknesses of the front and the rear plates are 3 mm and 9 mm, respectively. However, for the pressure-drop experiments the thicknesses of the front and rear plates are 3 mm and 6 mm, respectively. Also, it should be noted that for the case of the pressure-drop experiments the rear plate of the target assembly has a higher acoustic impedance (tool-steel plate) when compared to the front target plate (Al plate).

Both sides of the flyer and the target plates are ground flat by using a surface grinder to within 2.5 μm across the diameter. They are then lapped to within 2–3 Newton’s rings over the diameter. Lapping is carried out on a Lapmaster machine using a slurry of 14.5 μm aluminum oxide powder in mineral oil. To observe the Newton’s ring, the surfaces of the plates are polished on Texmeth cloth using 3 μm diamond paste. Special radial slots are milled on the periphery of the front and rear plates of the sandwich configuration to house the four voltage biased copper pins. These are electrically insulated from the target and are glued in the slots with non-conductive epoxy. These pins are then ground and lapped flush with the surface of the front plate. The first contact of any of these pins is used as a signal to trigger the oscilloscope and to determine the tilt between the flyer and the target assembly. In order to measure the combined normal and transverse particle displacement at the rear surface of the rear plate, a holographic diffraction grating with 1200 lines mm⁻¹ is used.

**Kinematics of Combined Compression-and-Shear**

**Finite Deformations**

Before analyzing the wave propagation in the flyer and target plates, it is important to analyze the kinematics of the pressure-shear finite deformation occurring within the sandwich specimen. The analysis confirms that once a nominally homogeneous stress-state has developed within the specimen, the shear deformation of the specimen is essentially simple shear.

For the combined compression-and-shear plate-impact experiments the total deformation applied to the specimen consists of two parts: (a) a state of compression at the arrival of the compressive longitudinal wave; and (b) a state of simple shearing after the arrival of the transverse wave at the specimen plane. Upon arrival of the compressive wave at the specimen plane, the deformation gradient tensor \( F^c \) can be expressed as

\[
F^c(t) = \begin{bmatrix}
\dot{\lambda}(t) & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  

(2)

where, \( \dot{\lambda}(t) \) is the axial stretch in the specimen due to compression.

The shearing deformation occurs at the arrival of the shear wave at the specimen plane, and can be represented in terms of the shear-strain \( \gamma(t) \), as

\[
F(t) = \begin{bmatrix}
\dot{\lambda}(t) & 0 & 0 \\
\gamma(t) \dot{\lambda}(t) & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  

(3)

Then, the total deformation gradient tensor, \( F \), can be expressed as \( F = F^c F^s \), or

\[
F(t) = \begin{bmatrix}
\dot{\lambda}(t) & 0 & 0 \\
\gamma(t) \dot{\lambda}(t) & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  

(4)

Computing the inverse and the rate of change of the deformation gradient tensor \( F \), the velocity gradient, \( L \), can be expressed as

\[
L = \dot{F} F^{-1} = \begin{bmatrix}
\dot{\lambda}/\dot{\lambda} & 0 & 0 \\
\gamma + \gamma (\dot{\lambda}/\dot{\lambda}) \dot{\gamma} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]  

(5)

Note that the rate of deformation tensor, \( D \), is the symmetric part of the velocity gradient tensor, \( L \), i.e., \( D = \frac{1}{2} [L + L^T] \), and can be expressed as

\[
D = \frac{1}{2} \begin{bmatrix}
2\dot{\lambda}/\dot{\lambda} & \gamma + \gamma (\dot{\lambda}/\dot{\lambda}) & 0 \\
\gamma + \gamma (\dot{\lambda}/\dot{\lambda}) & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]  

(6)

In a typical plate-impact compression-and-shear experiment considered here, by the time the shear deformation is imposed, a nominally homogeneous normal stress state is present, i.e. \( \dot{\lambda}/\dot{\lambda} \to 0 \). In view of this, the rate of deformation tensor represents simple shear deformation rate, with shearing in the 1–2 plane, i.e.

\[
D = \frac{1}{2} \begin{bmatrix}
0 & \dot{\gamma} & 0 \\
\dot{\gamma} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]  

(7)

**Wave Propagation in the Flyer and the Target Plates:**

**High-Strain-Rate Combined Pressure-and-Shear Experiments at Constant Normal Pressure**

Figure 8 shows the time–distance diagram detailing wave propagation in the flyer and target plates for the high-strain-rate combined pressure-and-shear plate impact experiments at constant normal stress. The abscissa represents the spatial position of the wave front at any instant of time while the ordinate represents the temporal location of the wave front. When the flyer plate impacts the target plate both longitudinal and shear waves are
generated in the flyer as well as the target plates. The solid lines represent the longitudinal wave fronts while the dashed lines represent the shear wave fronts. The slopes of the solid and the dashed lines represent the inverse of the longitudinal and the shear wave speeds, respectively.

Since the longitudinal waves propagate faster than the shear waves, they arrive at the specimen plane first. Upon arrival, because of the impedance mismatch between the front target plate and the polymer specimen, part of the longitudinal wave is reflected back towards the flyer/target impact face while the rest passes through into the specimen. Since both the front and the rear target plates have acoustic impedance higher than the specimen, the longitudinal wave reverberates several times between the front and the rear target plates until a nominally homogenous compressive state-of-stress is attained within the specimen. The longitudinal wave arrives at the free surface of the target plate at time $T_A$. After reflecting from the rear surface the compressive wave is transformed into a release wave that travels back toward the specimen. Since the front and the rear plates of the target assembly are made from the same material and the two plates remain elastic during the experiment, the arrival of the release wave at the specimen plane results in a complete unloading of the state of compression within the specimen. This occurs at the time indicated by $T_C$ on the time–distance diagram. As mentioned earlier, the thickness of the flyer plate is designed such that the time for longitudinal wave propagation through the thickness of the flyer is greater than the corresponding round trip time in the target assembly. Thus, during the time duration of the experiment, the reflected longitudinal wave from the flyer does not affect the state of stress in the specimen.

The shear wave arrives at the specimen plane after a state of essentially uniform normal stress has been attained within the specimen. Upon arrival, the shear wave reverberates within the specimen until a nominally homogenous shearing state develops within the specimen. The shear strength corresponds to the difference in transverse particle velocity across the specimen divided by the instantaneous thickness. The amplitude of the shear wave transmitted through the specimen is proportional to the shear strength of the PC specimen (see Eq. 9 below), and arrives at the rear surface of the target plate at time $T_B$. The end time of the experiment is shown on Fig. 8 by $T_E$, and represents the arrival of the shear wave at the rear surface of the target plate as the state of compression is removed from the specimen plane by the arrival of the release wave. Thus for a given diameter of the flyer and the target plates, the thickness of the front and the rear target plates are designed so as to maximize the time window, i.e. $(T_E - T_B)$.

Using the method of characteristics for 1-D hyperbolic wave equations, the normal pressure in the specimen can be expressed as

$$-\sigma(t) = \frac{1}{2}(\rho c_L)_{Tp} u_{fs}(t),$$

where $(\rho c_L)_{Tp}$ represents the longitudinal impedance of the rear-plate of the target assembly and $u_{fs}(t)$ is the measured normal component of the particle velocity at the free surface of the rear target plate.

The shear strength of the specimen is given by

$$\tau(t) = \frac{1}{2}(\rho c_S)_{Tp} v_{fs}(t),$$

where $(\rho c_S)_{Tp}$ represents the transverse impedance of the rear-plate of the target assembly and $v_{fs}(t)$ is the measured transverse component of the particle velocity at the free surface of the rear target plate.

The engineering shear strain rate in the specimen is given by

$$\dot{\gamma}(t) = \frac{v_0 - v_{fs}(t)}{h_0},$$

where $h_0$ is the initial thickness of the PC specimen, and $v_0$ is the transverse component of the particle velocity of the flyer plate at impact.

The engineering shear-strain in the specimen is obtained by integrating the engineering shear strain rate over the time

$$\gamma(t) = \int_0^t \dot{\gamma}(t) dt.$$ 

For infinitesimal longitudinal deformation $h(t) \sim h_0$, and the engineering shear strain rate is also equal to the true shear strain-rate. However, for arbitrarily large deformations the true shear-strain is obtained from the knowledge of the current thickness of the specimen $h(t) = \lambda(t) h_0$, where $\lambda(t)$ is the actual stretch (compression) during the pressure-shear loading.
The time history of the axial stretch due to the applied normal stress at the specimen plane can be estimated by noting that the normal component of the particle velocity can be expressed as

\[ u_{fs}(t) = \varepsilon(t)C_L = (1 - \dot{\lambda}(t))c_L, \quad (12) \]

where, \( \varepsilon(t) \) is the normal strain in the specimen.

Using Eq. 12, the stretch in the specimen can be expressed in terms of the stress as

\[ \dot{\lambda}(t) = 1 - \frac{u_{fs}(t)}{c_L}, \quad (13) \]

And the instantaneous thickness of the specimen as

\[ h(t) = \lambda(t)h_0 = \left(1 - \frac{1}{2} \frac{u_{fs}(t)}{c_L} \right)h_0. \quad (14) \]

Alternatively, the time-history of the thickness of the specimen during compression can be obtained from the difference of the particle velocities on either side of the specimen as

\[ h(t) - h_0 = \int_0^t (u^+(\tau) - u^-(\tau))d\tau. \quad (15) \]

The history of the particle velocity to the right of the specimen, \( u^+(t) \), can be obtained from the measured particle velocity at the free surface of the target plate. However, the history of particle velocity \( u^-(t) \) to the left of the specimen is an unknown, and can be best estimated to be equal to the normal component of the projectile velocity, to yield

\[ h(t) - h_0 = \int_0^t (u_{fs}(t) - V_o \cos \theta)dt. \quad (16) \]

**Wave Propagation in the Flyer and Target Plates: High-Strain-Rate Combined Pressure-and-Shear Configuration With a Sudden Change in Hydrostatic Pressure**

The time–distance diagram for the high-strain-rate plate-impact combined pressure-and-shear experiment with a normal stress drop is shown in Fig. 9. In this case, unlike the high strain-rate constant normal stress configuration, a higher impedance CH tool-steel plate is employed as the rear plate in the target assembly. As a result, when the unloading wave from the free surface of the rear target plate arrives at the specimen plane, it results in a drop in normal stress by a factor governed by the ratio of the impedances of the front and the rear plates sandwiching the specimen. Using the method of characteristics, the drop in the normal pressure between state 1 and 2 for the aluminum/tool-steel target assembly can be obtained as 0.6. Thus, in the pressure-drop pressure-shear experiments, during the time interval represented by \( T_B \) to \( T_D \), the measured transverse particle velocity represents the shearing deformation of the specimen at constant normal stress corresponding to State 1, and then from \( T_B \) to \( T_C \) as the shearing deformation of PC at the reduced normal stress (State 2).

For the pressure-shear experiments with the step pressure drop the normal pressure at the specimen plane is given by

\[ -\sigma(t) = \frac{\rho c_L}{\rho_{cl}c_{cl} + \rho_{cl}c_{cl}} u_{fs} \quad (17) \]

where \( \rho c_L \) represents the longitudinal impedance of the front-plate and \( \rho u_{fs} \) represents the transverse impedance of the rear-plate of the target assembly, and \( u_{fs} \) represents the normal component of the particle velocity of the flyer.

The shear strength of the specimen is given by

\[ \tau(t) = \frac{1}{2} \rho c_L v_{fs}(t), \quad (18) \]

where \( v_{fs}(t) \) represents the measured transverse component of the particle velocity at the free surface of the rear target plate in State 2.

The nominal shearing rate in the specimen is given by

\[ \dot{\gamma}(t) = \frac{1}{h(t)} \left( V_o - \frac{1}{2} \left[ 1 + \frac{\rho c_L}{\rho c_L} v_{fs}(t) \right] \right). \quad (19) \]

The shear strain in the specimen is obtained by integrating the shear rate over the time of observation.
EXPERIMENTAL RESULTS AND DISCUSSION

High Strain Rate Compression-and-Shear Experiments at Constant Normal Stress

The objective of this series of experiments was to understand the shearing resistance of PC under ultra-high shearing rates and high hydrostatic pressures. Figure 10 shows the results of a typical high-strain-rate plate-impact pressure-shear experiment. The x-axis represents the shear-strain while the ordinate represents the shear-stress in the PC specimen. During deformation, the normal stress on the specimen was 0.74 GPa. Based on the transverse impedances of the Al target plates and the PC specimen, it takes about 150 ns for a state of simple shear to develop within the PC specimen. The shear rate during this combined pressure-and-shear loading is \(2 \times 10^5 \text{ s}^{-1}\). It is important to note that by the time the shear-wave arrives at the specimen plane a state of essentially homogeneous normal stress is developed within the specimen. The magnitude of the shear wave, as it travels through the PC specimen, attenuates quickly due to plastic flow. The plastic flow also reduces the difference amongst the normal stress components, leading to \(\sigma_{22} = \sigma_{33} \approx \sigma_{11}\). As a result, the time history of the hydrostatic pressure, i.e., \(\sigma_m = \text{trace}(\sigma)/3 = (\sigma_{11} + \sigma_{22} + \sigma_{33})/3\), for the combined pressure-and-shear plate impact experiments under consideration here, becomes very similar to that of the normal stress, with \(\sigma_{11} \approx \sigma_m\) [41]. The equivalent shear stress then becomes identical to the shear stress, i.e., \(\tau\). In this way, the hydrostatic pressure in the specimen becomes virtually equal to the normal impact stress \(\sigma_{11}\), and the deformation state within the specimen is one of a simple shear under a known hydrostatic pressure.

The flow characteristics of PC under the combined pressure-and-shear loading at ultra-high shearing rates are significantly different when compared to those observed under uniaxial compression using the SHPB. Note that much of the rise in the early part of the curves is associated with the ring up of the low-impedance sample sandwiched between two high impedance plates. Nevertheless, at least the latter half of the measured profiles should provide a good indication of the shearing resistance of the sample. The yield stress in shear as well as in the flow stress at all levels of plastic strains is much higher than those observed in the SHPB experiments. This is to be expected since both the plastic shearing rate as well as the hydrostatic pressure is known to have a positive effect on the shearing resistance of amorphous polymeric materials. Also, it is interesting to note the absence of strain softening following yield during the high-strain-rate combined pressure-and-shear deformation. In fact the flow stress shows hardening from the very beginning, which continues throughout the entire duration of the experiment. It must be noted that during quasi-static deformation, the observed strain softening was understood to be due to a decrease in the intermolecular barriers to chain segment rotation with accumulation of plastic strain. However, during the high pressure and high strain-rate deformation conditions present in the present plate impact experiments, the mobility of the molecular chains including the chain segment rotations are expected to be suppressed, leading to the absence of strain softening immediately following yield during the high rate deformation. In this way, the results indicate very different deformation mechanisms to be operative in the PC at the ultra-high shearing rates imposed by the combined pressure-and-shear plate impact experiments when compared to its deformation under uniaxial compression employing the SHPB.

High Strain Rate Plate-Impact Combined Compression-and-Shear Experimental Configuration With a Normal Stress Drop

In the present study, in addition to the high strain rate combined pressure-and-shear plate impact experiments conducted at a constant normal stress (hydrostatic pressure), combined pressure-and-shear plate impact experiments that include a sudden alteration in normal stress (hydrostatic pressure) were designed and conducted. The objective of these experiments was to better understand the coupling between volumetric and shear deformation in PC at ultra-high shearing rates. In order to conduct these experiments, a 7075-T6 flyer along with a 7075-T6 front target plate and a CH tool-steel rear target plate were used. As discussed earlier, the difference in acoustic impedance between the front and rear target plates results in a drop in normal stress at the specimen plane during the high strain rate deformation process. In view of the choice of front and rear target plates utilized in the present experiments, the normal stress in the specimen, at the arrival of the reflected unloading longitudinal pulse, drops
TABLE 4. Summary of the constant pressure tests for the high-strain-rate pressure-shear experiments with pressure change.

<table>
<thead>
<tr>
<th>Shot no.</th>
<th>Projectile velocity (m s$^{-1}$)</th>
<th>Pressure, State 1 (GPa)</th>
<th>Pressure, State 2 (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD01</td>
<td>93.2</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>PD02</td>
<td>80.9</td>
<td>0.88</td>
<td>0.5</td>
</tr>
</tbody>
</table>

to $\sigma_2 \sim 0.6 \sigma_1$. The summary of the high strain rate plate-impact experiments with a normal stress (hydrostatic pressure) drop is presented in Table 4. Shot PD01 was conducted at an impact velocity of 93.2 m s$^{-1}$ while Shot PD02 was conducted at an impact velocity of 80.9 m s$^{-1}$.

Figure 11 shows the history of normal stress, shear stress, and the resulting shear strain-rate within the specimen obtained during the high-strain-rate pressure-shear experiment PD02 with a normal stress (hydrostatic pressure) drop. The abscissa shows the time after the arrival of the longitudinal wave at the specimen plane, while the ordinate represents the magnitude of the normal and the shear stress in the specimen. Upon arrival of the longitudinal wave at the specimen plane, the normal stress in the specimen builds up to a level of approximately 0.88 GPa in about a microsecond. The details of the stress build-up can be seen as a sequence of steps in the normal stress profile before the stress reaches a plateau. The normal stress remains constant at that level thereafter. At about 2.2 $\mu$s, the release wave from the rear surface of the target plate arrives at the specimen plane, resulting in a normal stress (hydrostatic pressure) drop from 0.88 GPa to 0.5 GPa. This drop in stress is due to the impedance mismatch between the front and the rear target plates comprising the target assembly, and occurs in a series of steps as shown in the unloading profile. Since the wave speed of the transverse waves in the front plate is much smaller than the longitudinal wave speed, the shear wave arrives at the specimen plane at approximately 1 $\mu$s after the arrival of the loading compressive pulse at the specimen plane. It is important to note that by the time the transverse wave arrives at the specimen plane, the normal stress has already stabilized to a constant level, and at the arrival of the shear wave the specimen undergoes combined pressure-and-shear deformation at an essentially constant normal stress. The shearing rate during this deformation process remains essentially constant at $1 - 2 \times 10^5$ s$^{-1}$ during the duration of the experiment.

Figure 12 shows the history of shear stress, shear strain rate, and the normal stress (hydrostatic pressure) as a function of shear strain in the PC specimen for Shot PD02. As noted earlier, the three phases observed during dynamic uniaxial compression are absent and the material continues to harden after yield. In response to the abrupt change in normal stress (hydrostatic pressure), the shear strength of PC initially decreases, reaches a plateau, and then resumes strain hardening with further accumulation of shear strain. This behavior is especially interesting in view of the known shearing behavior of metallic engineering materials, which are essentially insensitive to changes in applied pressure, and sheds light on the coupling between equi-voluminal and volumetric deformation for glassy polymers at ultra-high shearing rates in which the relaxation of the molecular chains due to a reduction in hydrostatic pressure leads to a corresponding reduction in shearing resistance.

Figure 13 shows the history of shear stress, the shear strain-rate, and the normal stress as a function of shear...
strain on the PC specimen for Shot PD01. As also noted for the case of Shot PD02, the three phases observed during dynamic uniaxial compression are absent and the material continues to harden after yield. In response to the change in pressure, the shear strength of PC initially decreases, reaches a plateau, and then resumes strain hardening with further accumulation of shear strain. Figure 14 shows the stretch (compressibility) of PC specimen as a function of elapsed time after the arrival of the longitudinal wave at the specimen plane. The history of stretch is obtained by using Eq. 13. The specimen compresses rapidly at the arrival of the compressive longitudinal loading pulse, and the stretch reaches a level of 0.89 as the normal stress (hydrostatic pressure) stabilizes at about 0.88 GPa. As the unloading wave arrives at the specimen plane, the normal stress (hydrostatic pressure) in the specimen drops from 0.88 GPa to 0.5 GPa. In response to this drop in normal stress, the specimen relaxes and regains a part of its original thickness. This is observed in Fig. 14 as a reversal of stretch at approximately 2 μs. Thereafter, the thickness of the specimen remains nearly constant for the rest of the experiment.

**SUMMARY AND CONCLUSIONS FROM THE WORK**

In the present study, we provide results of both quasi-static and high-strain-rate tests conducted to better understand the yield and flow response of amorphous PC as a function of strain, strain-rate, and normal stress (hydrostatic pressure). The quasi-static response of PC is obtained by using a servo-hydraulic test machine at strain rates in the range from 0.001 to 0.002 s⁻¹. Using the SHPB nearly adiabatic compression tests are conducted in the intermediate strain-rate regime (ranging from 10⁵ to 10⁶ s⁻¹). The results of the quasi-static and the SHPB adiabatic tests provide further confirmation of what has been observed in the past by other investigators, i.e., (a) three distinct phases are observed during quasi-static and dynamic deformation of PC, i.e., initial elastic and non-linear viscoelastic behavior leading to yield, strain softening, and work hardening, (b) the yield strengths at the elevated strain rates are much higher than the yield strength under quasi-static loading conditions, and (c) the flow stress at elevated strain rates is much higher than the flow stress at quasi-static strain rates at all levels of plastic strains. Since temperature is understood to play an important role in governing the dynamic response of polymers, nearly isothermal tests were also conducted by employing incremental compression tests in the SHPB. The dynamic flow behavior observed under isothermal and adiabatic conditions is quite similar, so much so that the adiabatic and isothermal tests at strain-rates of approximately 1750 s⁻¹ almost overlap each other. The nearly similar dynamic mechanical response of PC at low to moderate strain rates is understood to be because of the relative lack of temperature sensitivity of the storage modulus in the α-regime, as measured by the DMA from 0 to 25°C (the storage modulus of PC only decreases by 3% [37]), and due to restrictions of the β-motion at the elevated strain rates. These molecular level constraints ensure that most of the inelastic energy is stored as deformation energy and there is little change in dissipation energy with strain rate.

In order to investigate the behavior of PC under multi-axial loading conditions and at strain-rates in the range of 10⁵–10⁶ s⁻¹, high-strain-rate pressure-shear plate-impact experiments were conducted. The motivation for these combined pressure-shear experiments stems from some recent studies, which indicate that the shear behavior of polymers is clearly influenced by dilatation. Consequently,
Besides the traditional uniaxial laboratory experiments, experiments on specimens subjected to multi-axial stresses are necessary to begin understanding how to characterize the corresponding time-dependent behavior of polymeric materials. In these high strain rate combined pressure-and-shear plate impact experiments thin films of PC were sandwiched between two hard elastic plates and impacted by an elastic flyer plate in a pressure-shear configuration. Moreover, by employing a suitable combination of front and the rear target plates, a sudden alteration in normal stress (hydrostatic pressure) was induced during the high-strain-rate shearing process. The step-drop in normal stress (hydrostatic pressure) allows the investigation of coupling between volumetric and equivoluminal (shear) deformations for glassy polymers.

The results of a typical high strain rate plate impact combined-pressure-and-shear experiments indicate that the shearing resistance of PC at ultra-high shearing rates is significantly different when compared to that obtained at intermediate strain-rates using the SHPB. The yield stress and the flow stress levels are much higher than that observed in the SHPB experiments at all levels of plastic strain, and confirm the presence of strong positive effects of high shearing rates as well as hydrostatic pressure on the shearing resistance of the amorphous polymers. Again, it is interesting to note the absence of strain softening following yield during the pressure-shear deformation. In fact the flow stress shows hardening from the very beginning and continues through the entire duration of the experiment. In response to the change (drop) in hydrostatic pressure, the amorphous PC shows considerable pressure-sensitivity, and the shear strength of the PC is observed to drop and then again resume strain hardening corresponding to the new level of the applied normal pressure.

The results obtained from these experiments provide valuable information to critically examine existing deformation models at ultra-high shearing rates for amorphous polymeric materials that involve coupling between volumetric and equivoluminal deformations, and are expected to provide guidelines for the development of new ones.

REFERENCES