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Use of Taylor Rod-on-Anvil Impact Experiments to Investigate High Strain Rate Behavior in Polyolefins

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Abstract. Taylor rod-on-anvil impact experiments have been performed on a range of polyolefins. At impact velocity greater than ~250 m/s there are significant differences observed in the deformation behavior between the four polymers, which cannot be explained based on current understanding. During the initial stages of impact, mechno-luminescence is observed in all polymers and at all impact velocities. The location and length scale of this luminescence is consistent with the observed location of temperature increases that approach, and in some instances, exceed the melt point of the polymers.

INTRODUCTION

Polymers are widely used in numerous applications where they experience deformation events that occur at extremely high strain rates, i.e. ballistic events. Numerous observations and macroscopic descriptions of the response of polymers to these ballistic strain rates have been reported (see for example Bourne[1]). Comparison between three different grades of polyethylene using Taylor impact measurements have previously been conducted by Brown et al,[2] who showed that whilst UHMWPE or PEX (cross-linked PE) are similar they have significant differences to HDPE. However, the underlying molecular mechanism of the polymers under these extreme conditions is still poorly understood. Polyolefins are by far the most produced polymers globally and are used in diverse applications from consumer goods to biomedical implants. Despite their deceptively simple molecular structure, the relationships between the mechanical behavior and molecular structure are not fully understood and this becomes more evident in their behavior at high strain rates. To address these issues it is necessary to utilize higher speed impact experiments than those accessible using the commonly used Izod or Charpy impact tests. Two of the most common approaches are the split Hopkinson bar and the Taylor impact tests. In this communication we summarize the results of a study of several grades of polyolefin using Taylor rod-on-anvil impact experiments, in which the impacted samples are deformed under uniaxial stress.

EXPERIMENTAL

Taylor rod on anvil impact tests were conducted on commercial grades of three different polyethylenes – LDPE, HDPE and UHWMPE – and polypropylene (PP). Samples were cut and shaped into cylinders 30 mm in length and 7.62 mm in diameter using a lathe. Tests were performed using the 7.62-mm single stage gas gun at Georgia Tech, at speeds between 50 and 500 m/s by varying the pressure of compressed helium accumulated in a valve-controlled

chamber behind the projectile. The samples were propelled along the 2 m long barrel towards a polished hardened steel anvil. The sample velocities were determined as they exited the barrel via a laser beam interruption method consisting of two lasers. High-speed optical imaging of the sample impacting onto the anvil was used in conjunction with diffuse back lighting to obtain the side profile of the samples as a function of time during the impact event. Imaging was done using a high-speed video (NAC HX7) running at a frame rate of 150,000 s^{-1} and an IMACON-200 camera that takes 16 shots at pre-defined time intervals (typically using 250 ns shutter speed and a 0.5 µs delay between images). The camera and video are both mounted outside the impact chamber perpendicular to the sample flight path.

Spectroscopic data were collected in repeat measurements, where the hardened-steel anvil was replaced by polished sapphire, behind which a fiber optical cable was mounted and connected via a fiber-optical cable to a high speed spectrometer measuring over the wavelength range of 390-610 nm. The instrument collects the full wavelength range with a time resolution of 23 ns. Infra-red imaging of the impact events were also conducted using an IRC906 camera, which allows spatially resolved temperature data. The infra-red camera was positioned perpendicular to the projectile path and positioned in-line with the steel anvil impact face. With the camera operating at a maximum rate of 125 Hz, the IR images were obtained for the first 7.9 ms of the impact. The IR images were calibrated using the known temperatures of a blackbody placed at the anvil interface, with thermal images obtained over the same camera times as used in the impact experiments. The A/D intensity from the IR detector was measured using a 7.9 ms exposure from the blackbody with temperatures varying between 50 and 325 °C as determined by a thermocouple. The calibration curve was fitted using a cubic equation, from which the A/D counts gave a maximum error in temperature of ~6%.

Axial and longitudinal strain data were determined using an in-house written MatLab code that analyzes the line-edge profiles of the samples as a function of time from the high-speed video images captured during the impact event.

RESULTS AND DISCUSSION

The deformation of the various polyolefins during rod-on-anvil impact experiments, superficially follows similar behavior. As shown as an example of PP in Figure 1, during the compressive phase of the deformation following impact, when the trailing edge of the sample progressively moves towards the anvil face (i.e. in Fig. 1 at times less than ~70 µs), the sample predominantly deforms laterally i.e. perpendicular to impact direction. Little strain, however, is seen to be propagated backwards along the longitudinal length of the sample. The degree of lateral strain, and therefore the extent of maximum length reduction of the longitudinal sample length (see Fig. 2) increases with increasing impact velocity.
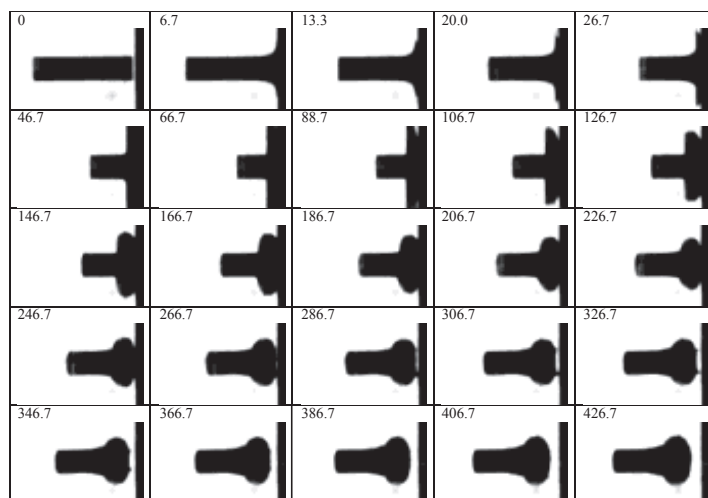
FIGURE 1. Compilation of images taken from a high-speed video of PP at an impact speed of 485 m/s. The numbers in the top left of each image are times in microseconds. Time zero in these images is taken to be immediately before the sample first impacts the anvil.

As can be seen in Fig. 2, the initial strain rate (during the compression phase of the impact) increases with increasing impact velocity. The dependence of strain rate with impact velocity is seen to have a linear logarithmic dependence, and within experimental error, it is similar for all four polyolefins. This suggests that the initial phase of the deformation following impact is dominated by the sample momentum, and is rather independent of the molecular structure. The maximum extent of strain for each of the polyolefins also shows a linear dependence on impact velocity. However, there is some variation in maximum strain between the different polymers, suggesting that as the momentum is dissipated during the compression, the molecular structure begins to dominate the behavior.
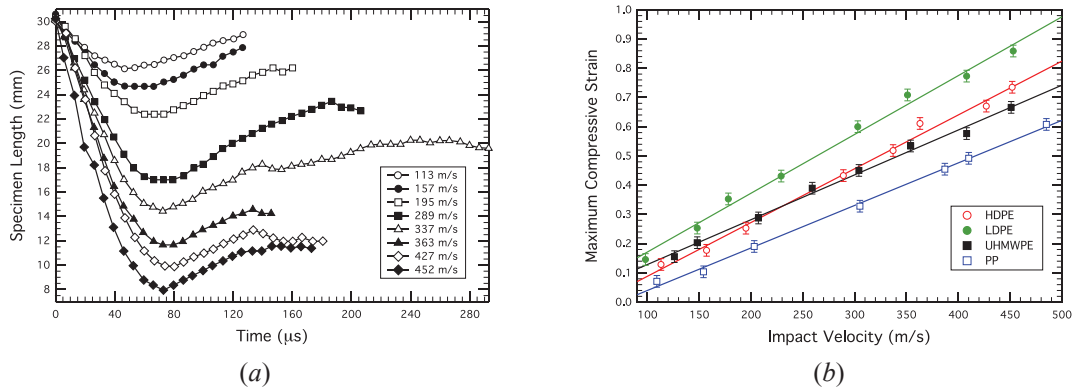
FIGURE 2. (*a*) Specimen length as a function of time during impact for HDPE samples at various initial impact velocities (as indicated in bottom right of figure). (*b*)

As the sample momentum is fully dissipated, it begins to rebound from the anvil and does so in a complex manner, which differs depending on the polymer. As shown in Fig. 1 for PP at an impact velocity of 485 m/s, this occurs for times greater than ~70 μs. The differences in the behavior between the polymers during this rebound phase reflects the differing natures of the polymer molecular structures. The behavior especially at medium to high impact velocities is very characteristic of the polymer. The dependence of strain rate as a function of impact velocity during rebound for the four polymers varies considerably.

Figure 3 shows a compilation of images for all four polyolefins recovered after impact as a function of impact velocity. Remarkably at low impact velocities it was observed that little plastic deformation of the sample has occurred, even though considerable amount of deformation is observed in samples when these polymers are deformed at much lower rates i.e. < 4 m/s. In fact, for all three polyethylenes impacted at ~100 m/s, it is almost impossible to visually tell if the sample has even been impacted, as there is almost no discernable change in the size, shape, or optical quality of the sample. Only in PP, is any visible effect observed with visible stress-induced whitening occurring at the impact face of the samples, which we believe is associated with cavitation occurring during impact. At higher impact velocities, for all the polymers, plastic deformation is evident, although the resulting shape following impact differs between the polymers and as a function of impact velocity. Despite the high degree of change in shape for HDPE, LDPE and PP, no failure i.e., cracking, is observed in these samples. By comparison UHMWPE does show failure at impact velocities exceeding ~250 m/s. However, comparison of the UHMWPE sample masses before and after testing showed that even in the cracked samples, there is very little or no discernable mass loss.

Whilst the NAC video imaging provides details of the overall shape changes over the whole impact event, much higher time resolution imaging is obtained using the IMACON. As shown in Fig. 4, at the onset of the impact event i.e., during the first few microseconds following impact, distinct mechano-luminescence is observed at the impact face of the sample. This effect was observed in all the four polyolefins at all impact velocities. The intensity of the mechano-luminescence is seen to increase with impact velocity, but the exact nature of this is difficult to determine from the current set-up as the maximum intensity at high impact velocities saturates the camera. However, the mechano-luminescence is only observed immediately after the onset of impact, i.e. ~ 0.5 μs after the samples first hit the anvil. The luminescence is only observed to last for ~1-2 μs, with the total time depending on the impact velocity. As can be seen from Fig. 4, and similarly with all the polymers and at all impact velocities, there is no discernable strain observed in the sample during the time period when the mechano-luminescence is observed. This phenomenon cannot therefore be associated with mechanical straining of the sample, but is a result of the shock

wave that propagates from the anvil through the polymer. If this is the case it is not clear why mechano-luminescence is only observed at the anvil-polymer interface, but could be caused by dissipation of the shock wave energy by the polymers as the wave propagates through the length of the sample.


FIGURE 3. Composite of images from HDPE, LDPE, UHMWPE and PP following impact experiments at velocities between 100 and 450 m/s. The black scale bar (lower left) is 10 mm.
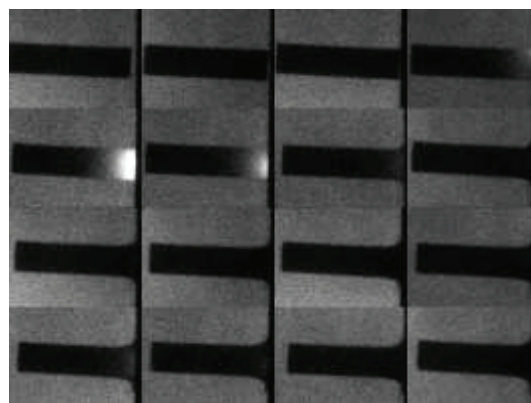

FIGURE 4. Compilation of IMACON images of HDPE at an impact velocity of 348 m/s. The sequence of images are 0.5 µs apart and each have an exposure of 250 ns. The observed mechanoluminescence is clearly visible in the 4th to 7th images.

The origin of the mechano-luminescence is not understood at present, but it seems plausible that it could be associated with chain scission. To help understand the origin of the mechano-luminescence, spectroscopic measurements were made during the impact events. A typical example of the spectroscopic data obtained is shown in Fig. 5, where a broad peak is observed between 400 and 560 nm. The peak intensity is seen to decrease with increasing impact velocity from ~490 nm to ~465 nm for HDPE, LDPE and PP (UHMWPE has not yet been tested spectroscopically). These peak values are equivalent to energies of 244 and 257 kJ/mol (i.e. 2.53 and 2.67 eV, respectively), which exceed literature values for C-C chain scission of 110kJ/mol in PE.[3]
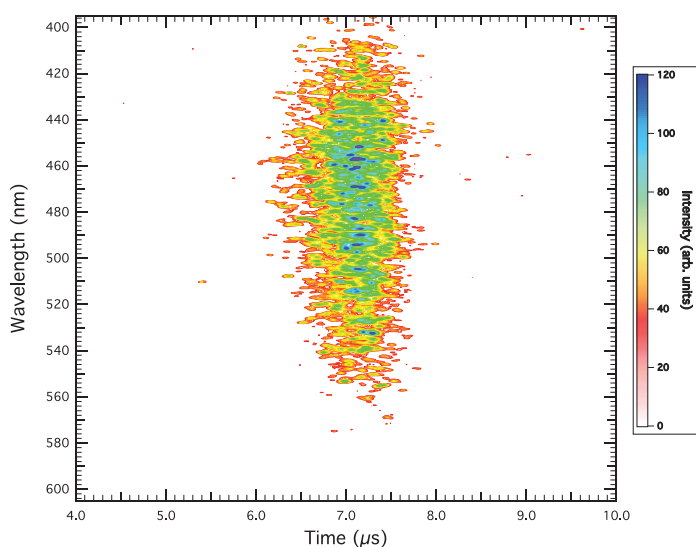
FIGURE 5. Contour plot of spectral emission as a function of time at beginning of impart event for LDPE at an impact velocity of 350 m/s. Time equal to zero is arbitrary and not consistent with impact time.

Comparisons to continuum mechanics descriptions of the impact behavior of the polymers is on-going, but it is quite clear that, the currently available constitutive models are only able to describe the general behavior of the polymers at low impact velocities. At medium to high impact velocities none of the currently available models are able to describe the observed deformation behavior seen in these polyolefins. One significant factor, which is clearly not accounted for entirely by the current continuum models is the very large observed temperature increases in the sample. Temperature increases of 62 K have been predicted in HDPE during ballistic impact.[4] However, as shown in Figure 6, the temperature rise approaches, and in some areas of the sample greatly exceeds, the melt point of the polymers (T_m for LDPE = 105-110 °C, HDPE = 130-137 °C and for PP = 130-170 °C depending on syndio-/iso-tactic content). However, as shown in Fig. 6(a), the temperature increases are highly localized to the initial impact zone of the sample, i.e. within a few millimeters from the initial impact zone, longitudinally. Despite the very large degree of lateral deformation, especially at high impact velocities, there is very little temperature increase beyond the initial sample diameter. This differs somewhat from the model predictions by Furmanski et al,[4] where temperature increases are predicted to extend further from the initial impact zone, both laterally and longitudinally, than those observed in our experiments. The lack of propagation of heat away from the impact area of the sample can perhaps be rationalized given the limited time of the impact event (few hundred microseconds) and also considering the high dielectric nature of these polymers. The temperature rise close to or exceeding the melt temperature of the polymers at this impact zone, even if very briefly, does help explain why current models of behavior do not work. We are actively working on incorporating these new data into our modeling efforts.
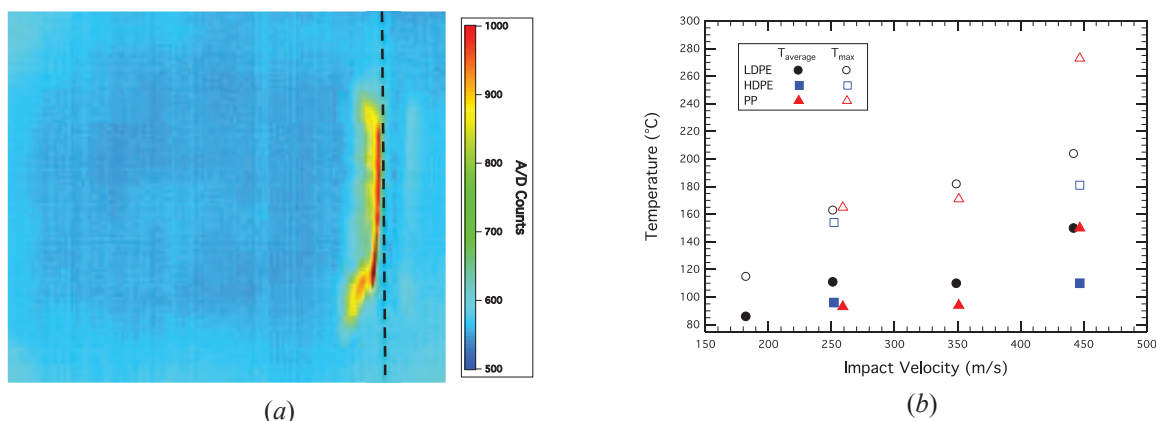
FIGURE 6. (a) IR thermal image of PP impact event at 447 m/s. The sample is invisible in this image, but is in the same orientation and direction of travel as shown in Fig. 1. The image represents the cumulative A/D counts over the entire impact event, as indicated by the color bar. The vertical black dotted line represents the position of the steel anvil face. (b) Plot of the average (elevated) temperatures observed during impact (closed symbols), and the peak maximum (open symbols) temperatures observed during the impact event.

CONCLUSIONS

In the four different polyolefins studied, we observe very different deformation behaviors, particularly at high impact velocities, and despite the similarity in the molecular structure of these polymers. During the initial phase of impact, mechano-luminescence of the samples is observed that is localized to the initial impact zone of the polymer. The luminescence is consistent with a broad spectral emission with peak energies that exceed literature values for C-C backbone chain scission energies for these polymers. Associated with this area of the sample, the temperature of the sample is seen to increase with increasing impact velocities to values that are close to, or in some areas of the sample, exceed the melt points of the polymers. Whilst we do not have a full understanding of the underlying mechanism, it is clear that the deformation processes are strongly influenced by quite subtle differences in the molecular structure of the polymer. Further studies are on-going.

ACKNOWLEDGEMENTS

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