Morphological changes in High-Density Polyethylene (HDPE) subjected to shock waves

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Abstract

The propagation of a shock wave front in a solid medium is characterized by an abrupt discontinuity in the thermodynamic properties of the material, notably pressure, internal energy, and specific volume[3]. The balance of mass, momentum, and energy that governs this phenomenon can be mathematically described by the Rankine–Hugoniot equations. For polymeric materials, the application of high pressures at high strain rates (10^6–10^8 s^{-1}), along with temperatures exceeding the melting point, leads to significant morphological changes; however, limited theoretical or experimental data is available in the literature. WAXS analysis shows significant differences in crystallinity and the presence of different crystalline phases depending on projectile velocities.
Keywords: high-density polyethylene, shock wave, morphology,

Introduction

The lightweight and flexible nature of thermoplastic polymers, along with their high impact resistance, makes them a feasible alternative to metals and ceramics. Polymer applications in the defense field are associated with high strain rates and shock wave phenomena, such as those caused by ballistic impacts on armor vests[1]. The study of the thermodynamic, mechanical, and morphological behavior of polymers under extreme conditions is rarely addressed in the literature. In this communication, high-density polyethylene (HDPE) samples were subjected to shock wave compression tests (flyer plate) at varying intensities. The estimated thermodynamic responses were calculated and compared with existing literature values[4,5], yielding consistent results. Synchrotron SAXS/WAXS measurements were performed on the samples in the normal direction (ND) relative to the shock wave. These results enable morphological characterization of the system at atomic and nanometric scales.

Methods and Materials

When a sabot/projectile system (Figure 1) impacts the target with a specific velocity (V_{mp}), pressure waves propagate through all plates. The Velocity Interferometer System for Any Reflector (VISAR) was used to measure the free surface velocity history (Figure 2), from which the HDPE equation of state and Hugoniot curve were derived. For the case of shock front propagation at velocity U_s, with particle velocity u_p and pressure P, the conservation laws of mass, momentum, and energy are applicable, as shown below[3]:

Mass: $\rho_0 Us = \rho.(U_s - u_p)$

Momentum: $P - P_0 = \rho_0.U_s.u_p$

Energy: $E - E_0 = (P-P_0).(V_0 - V)/2$

Equation of State: $U_s = C + S.u_p$

The subscript '0' refers to the conditions ahead of the shock front. The inverse plate impact test requires materials with a well-known equation of state to serve as the witness and backplate[6]. In this experiment, C45 steel was used.Literature reports that HDPE subjected to varying pressure, temperature, and stress can exhibit different polymorphic forms, including the monoclinic phase[2]. To investigate this, simultaneous SAXS/WAXS measurements were performed at the CoSAXS beamline of the MAX IV Laboratory synchrotron (wavelength = 1 Å; sample-detector distances: SAXS = 3 m, WAXS = 0.458 m). Post-impact samples exhibited asymmetric deformation (Figure 3). Therefore, different positions along each sample were analyzed (as shown in the schematic in Figure 3) to assess morphological variations across the surface. Data was collected via raster scanning (Np = 52 points per position) with an exposure time of 0.1 s. Fitky[7] was used for peak deconvolution, and MATLAB was used to calculate area and degree of crystallinity.

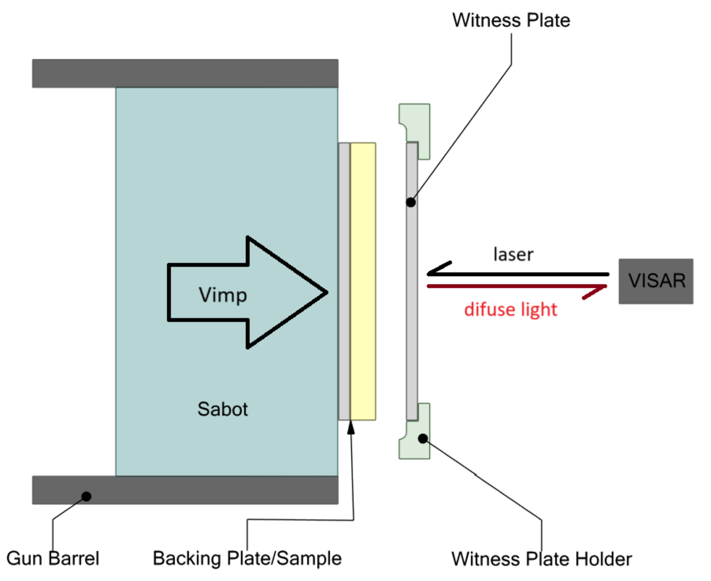

Figure 1. Inverse Plate Impact Scheme.

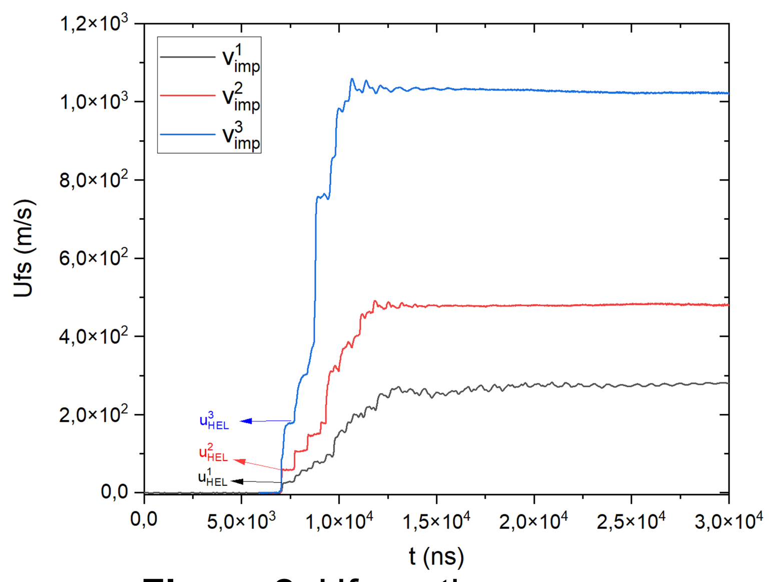

Figure 2. Ufs vs time curves

Results

At each Free Surface Velocity, U_{fs}, vs t, U_{fs2}, the first velocity of the plateau, was determined and, at this point, the Equation of State (EoS) and the Hugoniot Curve, Figure 4, were determined. These HDPE shock responses were compared with the literature and the results are consistent with previous work.
Figure 5 shows the Center Region diffractograms of the non-deformed sample and the three samples subjected to the plate impact test. In addition, the equations below were used to discuss the variation in the degree of crystallinity (X_c) and Monoclinic Phase (X_m), using V_{imp} and the position in the sample as comparison parameters:

$$X_c = \frac{A_{ort} + A_m}{A_{am} + A_{ort} + A_m}$$

$$X_m = \frac{A_m}{A_{am} + A_{ort} + A_m}$$

Here, A stands for area, and the subscripts denote the phase: amorphous (am), orthorhombic (ort), and monoclinic (m).

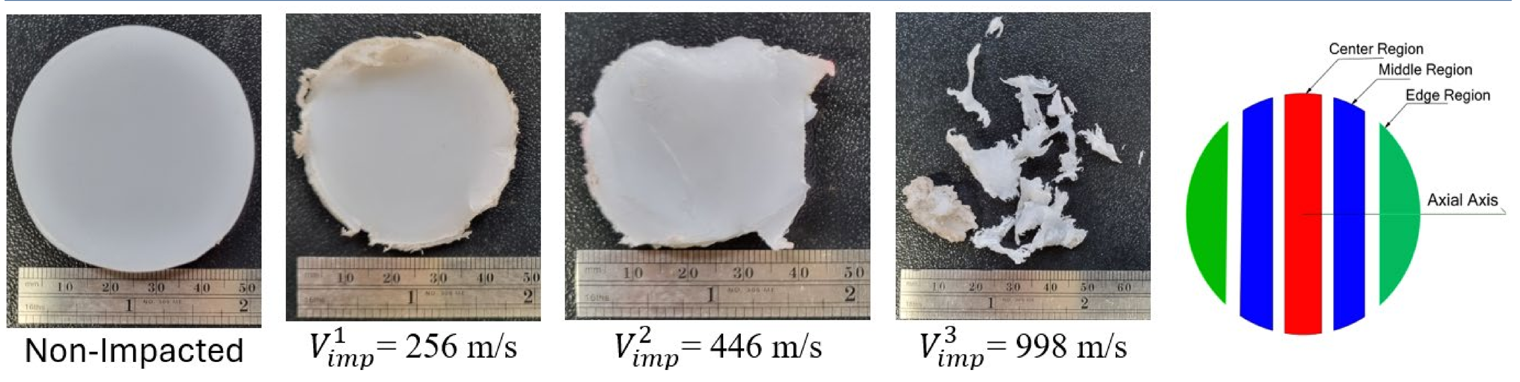

Figure 3. Post impacted samples and associated V_{imp}.

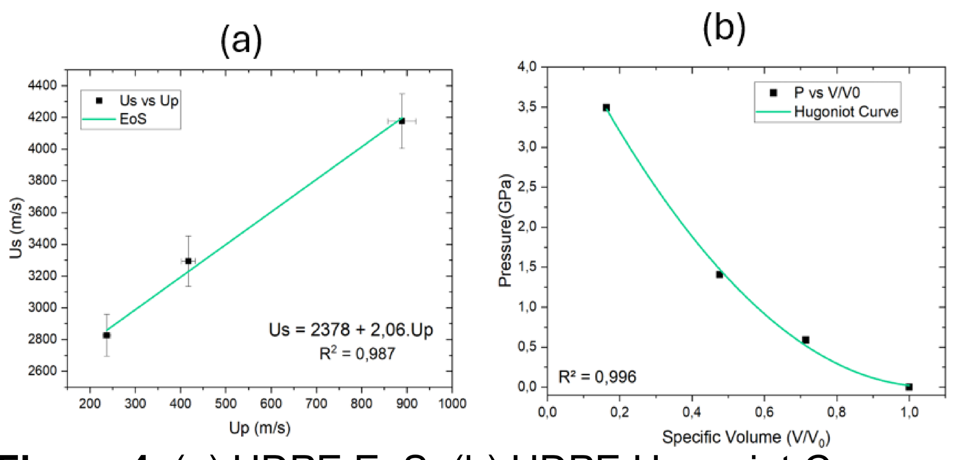

Figure 4. (a) HDPE EoS, (b) HDPE Hugoniot Curve

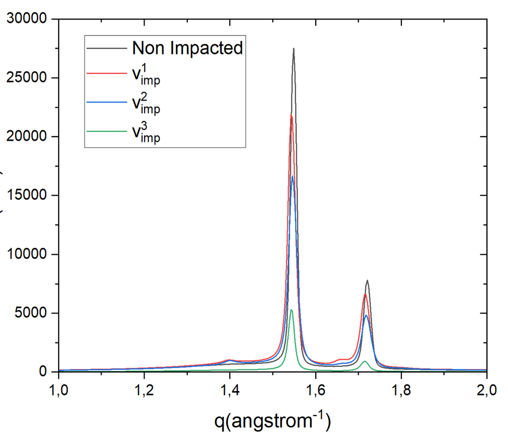

Figure 5. Diffractograms at different Impact Velocity

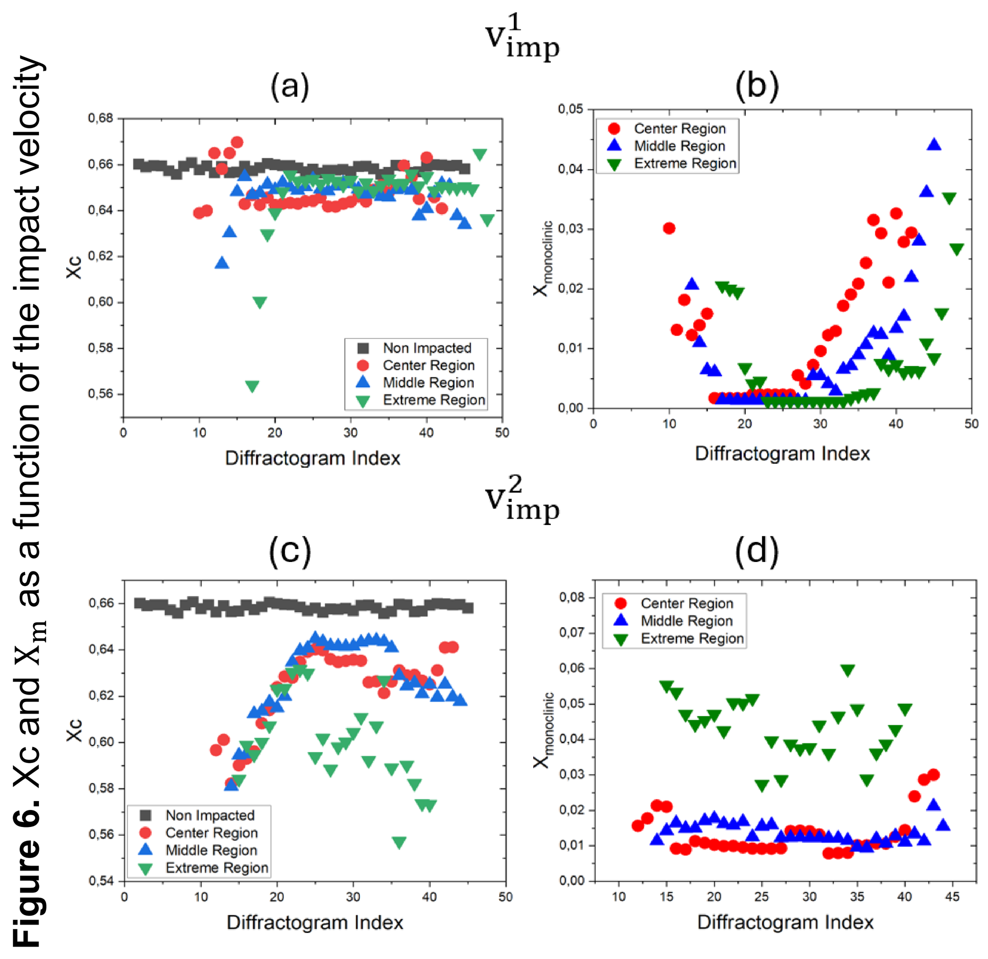

Figure 6. Xc and X_m as a function of the impact velocity

Discussion

Figure 5 displays the different diffractograms as a function of impact velocity. The monoclinic phase is present at velocities v^1_{imp} and v^2_{imp}, but absent at v^3_{imp}, mainly due to the melting and recrystallization process into the orthorhombic phase.
Figure 6 shows v^1_{imp} and v^2_{imp} samples using X_c and X_m to compare the center, middle, and edges regions of each sample. For v^1_{imp}, the two parameters are more uniformly distributed, with no significant Xc variation and the monoclinic phase tending towards the center. For v^2_{imp}, the edge region experiences considerable Xc loss and increased X_m, indicating that higher impact velocities leads to greater stress and temperature changes along the axial axis.

Conclusions

This study presented HDPE shock wave thermodynamical and structural responses. The post-impacted samples suggested a nonlinear axial and radial deformation. WAXS analysis shows the presence of orthorhombic and monoclinic phases, pointing out variation of crystallinity results with respect to axial position. The study of morphological changes continues with SAXS analysis undergoing, along with the development of a numerical modelling to understand the temperature distribution and HDPE mechanical behavior under high strain rate impact.

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