Chapter 9
Confined Compression of an IDOX–Estane Composite Cylinder under High-Strain-Rate Loading

Pooyan B. Javadzadeh, Ehsan Mehrdad, and Hongbing Lu

Abstract 5′-iodo-2-deoxyuridine (IDOX) has emerged as a suitable surrogate for plastic-bonded explosives (PBXs), for the investigation of mechanical behavior without the hazards associated with energetic materials. The material response under confinement is particularly important because it represents loading under realistic service conditions. In this work, a specimen-marking approach was implemented prior to testing to provide a consistent spatial registration framework for the subsequent simulation and modeling. The confined mechanical response of the particulate IDOX/Estane composite was characterized using a split Hopkinson pressure bar (SHPB) with passive stainless-steel confinement. Two foil strain gauges were attached on the outer surface of the confinement sleeve to measure hoop strain, to allow measurement of radial stress and characterization of the overall confined response of the particulate composite for which the initial internal structures were determined by x-ray micro-computed tomography.

Keyword Dynamic confined compression · SHPB · IDOX/Estane · Surrogate PBX 9501

Introduction

Surrogate plastic-bonded explosives (PBXs) have received increasing attention as safer alternatives for investigating the mechanical response of energetic materials, particularly PBX 9501. PBX 9501 is an insensitive high explosive composed of approximately 95 wt% particulate HMX, 2.5 wt% nitroplasticizer, and 2.5 wt% Estane binder [1, 2]. Among the proposed surrogates, IDOX has been shown to provide a reliable replacement for PBX 9501 [3, 4], and IDOX/Estane composites have demonstrated comparable mechanical behavior across a range of loading conditions, strain rates, and temperatures [5], [6]. Although most experimental studies on PBXs and their surrogates have focused on unconfined compression, confined compression; more representative of realistic service conditions has not been reported for IDOX/Estane composites. Recent work has primarily examined quasi-static and in-situ compression of IDOX/Estane for calibration of finite-strain phase-field models and backward digital volume correlation (DVC) frameworks [7, 8, 9].

In this study, passive confinement is employed to investigate the high strain-rate response of cylindrical IDOX/Estane composite specimens. Prior to testing, a novel specimen-marking approach as shown previously in [10] was implemented and combined with micro-X-ray computed tomography (μCT) scanning to characterize the initial internal structure, including void content and particle distribution. A conductive ink marker, visible under μCT and shown not to alter the mechanical response at room temperature, was used to provide a reliable registration feature for aligning pre-test scans. This approach addresses a long-standing challenge in simulation and modeling workflows, where accurate alignment of volumetric datasets is essential for specimen-specific analysis and validation.

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Paul Allison et al. (eds.), *Dynamic Behavior of Materials, Volume 1, 2026*, Conference Proceedings
of the Society for Experimental Mechanics Series, https://doi.org/10.13052/rp-9788743816249

Materials

IDOX grains of B1 size (75–150 μm) were used for specimen fabrication as outlined in [5, 11]. The material, supplied by Los Alamos National Laboratory (originally from Wilshire Technologies, Inc.), was recrystallized prior to processing. Recrystallization was performed by dissolving 1 g of IDOX in 100 mL of deionized water at 50 °C under continuous stirring, followed by controlled crystallization. The precipitated grains were filtered, rinsed with tetrahydrofuran (THF), and dried at room temperature. After drying, the grains were percussively ground to achieve the target size distribution and blended with Estane resin at a 19:1 grain-to-binder weight ratio. The mixture was loaded into a die preheated to 50 °C and consolidated at 155 MPa for 1 min. The pressed pellets were then extracted and machined to final specimen dimensions of approximately 12 mm in height and 12 mm in diameter. Figure 1 shows IDOX/Estane composite specimens under μCT, with visible ink marker line along longitudinal surface of the specimen.

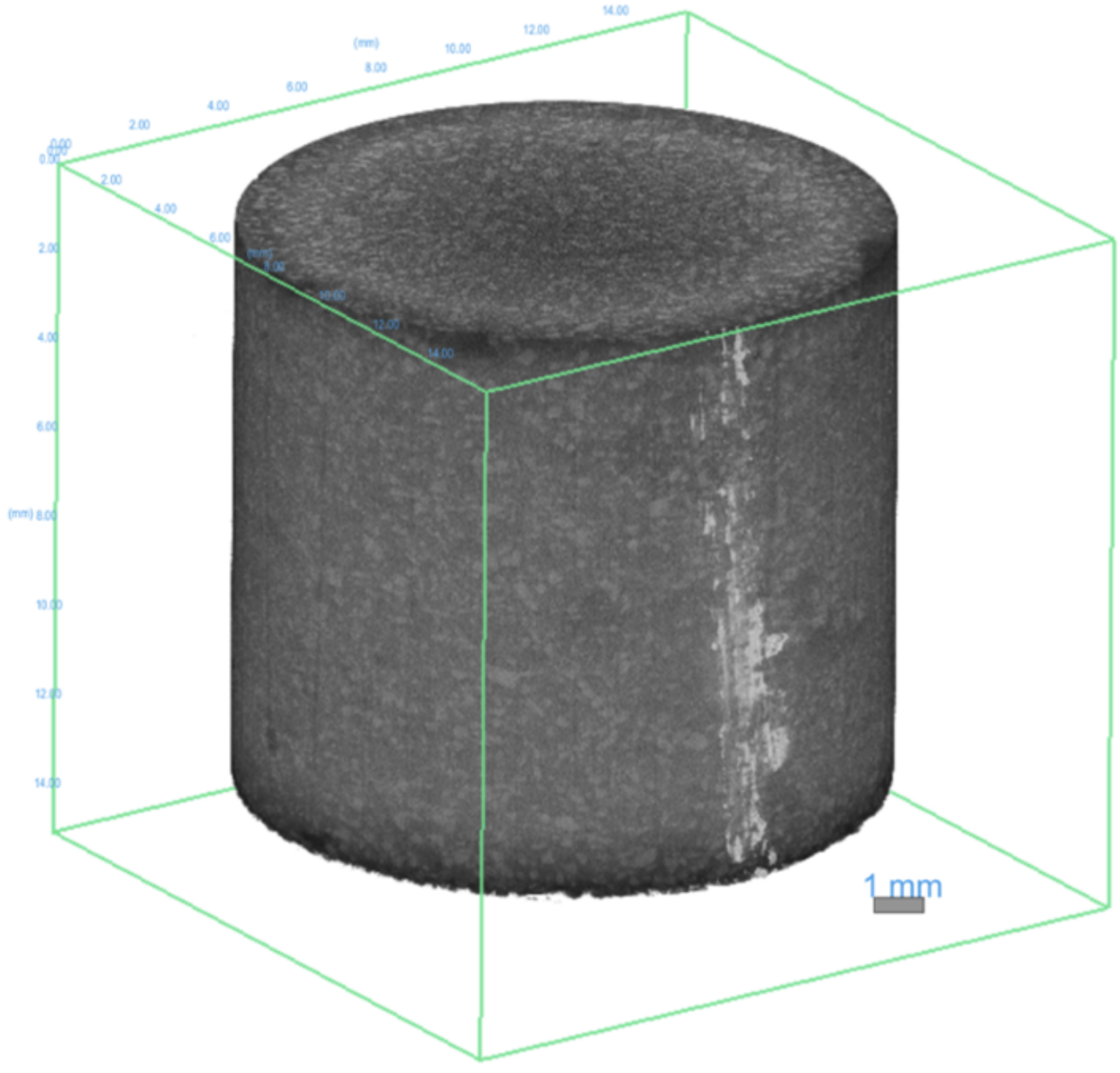

Fig. 1 μCT rendered image of IDOX/Estane composite under micro-CT with visible ink marker on the surface.

Experiment

A long SHPB was used to characterize three IDOX/Estane composite specimens under passive confinement. The apparatus consisted of an air reservoir, a 7.1 m gun barrel, a 0.91 m striker bar, an 8.7 m incident bar, and a 3.7 m transmission bar. The striker, incident, and transmission bars had a common diameter of 19 mm and were fabricated from 4340 steel. The bars possessed a Young's modulus of 200 GPa, density of 8000 kg/m^3, and an elastic wave speed of approximately 4950 m/s.

In SHPB experiments, achieving dynamic stress equilibrium in the specimen is critical. This equilibrium requires the elastic stress wave to travel through the specimen multiple times. Proper pulse shaping is essential to reach equilibrium conditions. Under dynamic equilibrium, one-dimensional stress wave analysis is applied to the bar data collected by strain gauges to calculate the strain rate, strain, and stress histories using the following equations, as detailed in reference [12]

$$\dot{\varepsilon}_{zz}(t) = \frac{C_0}{L_s}\left[\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)\right] \tag{1}$$

$$\varepsilon_{zz}(t) = \frac{C_0}{L_s}\int_0^t \left[\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)\right]dt \tag{2}$$

$$\sigma_{zz}(t) = \frac{A_0}{2A_s}E_0\left[\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)\right] \tag{3}$$

where $\varepsilon_i(t)$, $\varepsilon_r(t)$, and $\varepsilon_t(t)$ are the incident, reflected, and transmitted strain signals recorded by the strain gauges. The terms A_0, E_0, and C_0 denote the bar cross-sectional area, Young's modulus, and elastic wave speed, respectively. The specimen's initial cross-sectional area and length are given by A_s and L_s.

$$\sigma_{rr} = \sigma_{\theta\theta} = 0.5(\alpha^2 - 1)E_c E_h \tag{4}$$

$$\varepsilon_{rr} = \varepsilon_{\theta\theta} = 0.5\varepsilon_h\left[(1-\nu_c) + (1-\nu_c)\,\alpha^2\right] \tag{5}$$

where α is the ratio of the outer to inner diameters of the hollow cylinder; E_c and ν_c are the Young's modulus and Poisson's ratio of the confining steel cylinder, respectively; and ε_h is the measured circumferential strain on the outer surface of the hollow cylinder. The variables r and θ denote the polar coordinates defined in Fig. 2. The confinement sleeve used in

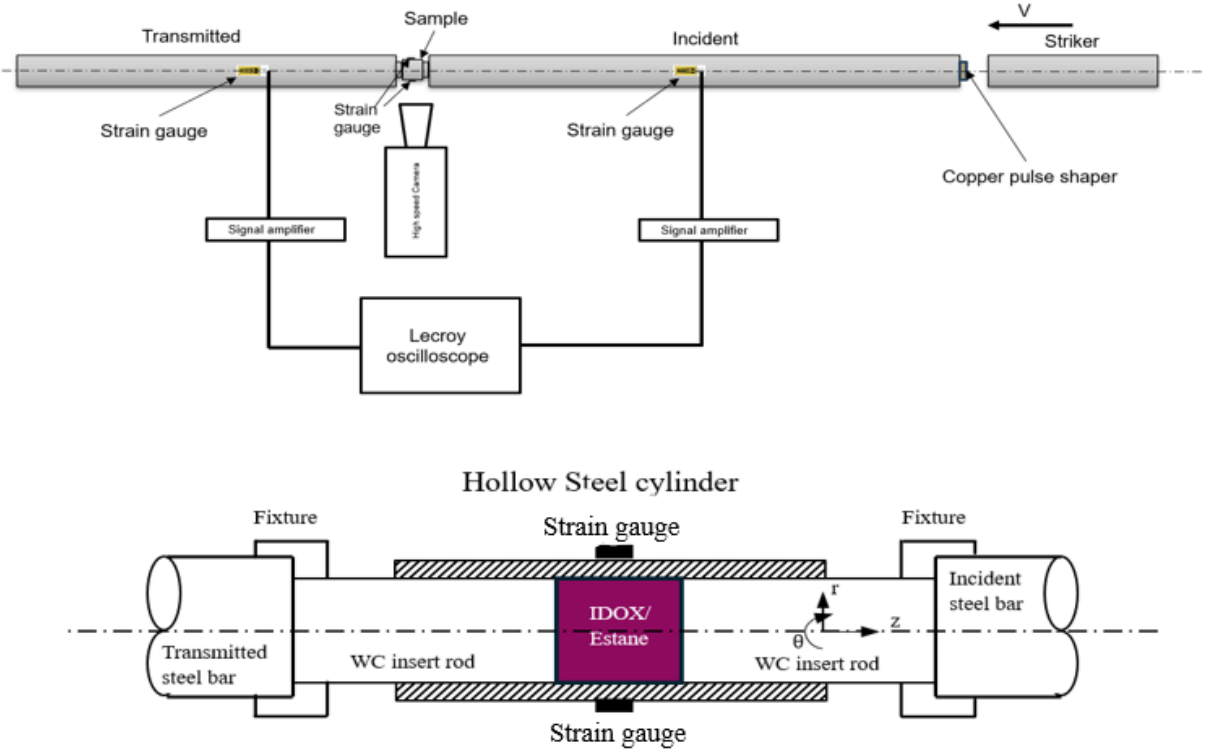

Fig. 2 Schematic diagram of the SHPB and passive confinement used in this work.

this study was manufactured from hardened AISI 4140 steel with a Young's modulus of 200 GPa and a Poisson's ratio of 0.29.

The passive confinement methodology originally developed by Ravi-Chandar et al. [13] for quasi-static compression of polymers was adapted here for dynamic compression of IDOX/Estane using the split Hopkinson pressure bar (SHPB) in order to characterize the hydrostatic and deviatoric response at high strain rates. Using the measured axial and confining stress–strain histories, the hydrostatic pressure (mean stress) σ_m and the volumetric strain ε_m are obtained as follows:

$$\sigma_m = \frac{1}{3}\left(\sigma_{zz} + 2\sigma_{rr}\right) \tag{6}$$

$$\varepsilon_m = \varepsilon_{zz} + 2\varepsilon_{rr} \tag{7}$$

The maximum shear stress τ_e, applied on any plane inclined at 45° angle with respect to the longitudinal (z) direction, and the maximum shear strain γ_e corresponding to τ_e , are given as:

$$\tau_e = 0.5\ \left(\sigma_{zz} - \sigma_{rr}\right) \tag{8}$$

$$\gamma_e = \left(\varepsilon_{zz} + \varepsilon_{rr}\right) \tag{9}$$

Results and Discussion

Figure 3 shows engineering stress–strain response of the confined IDOX/Estane composite cylinder obtained from the SHPB experiment at an average strain rate of approximately 120 s^{-1}. The material exhibits a strongly nonlinear response characterized by progressive stiffening with increasing strain, reflecting void collapse, particle rearrangement, and viscoelastic deformation of the binder under radial confinement. The specimen reaches a peak engineering stress of approximately 90 MPa

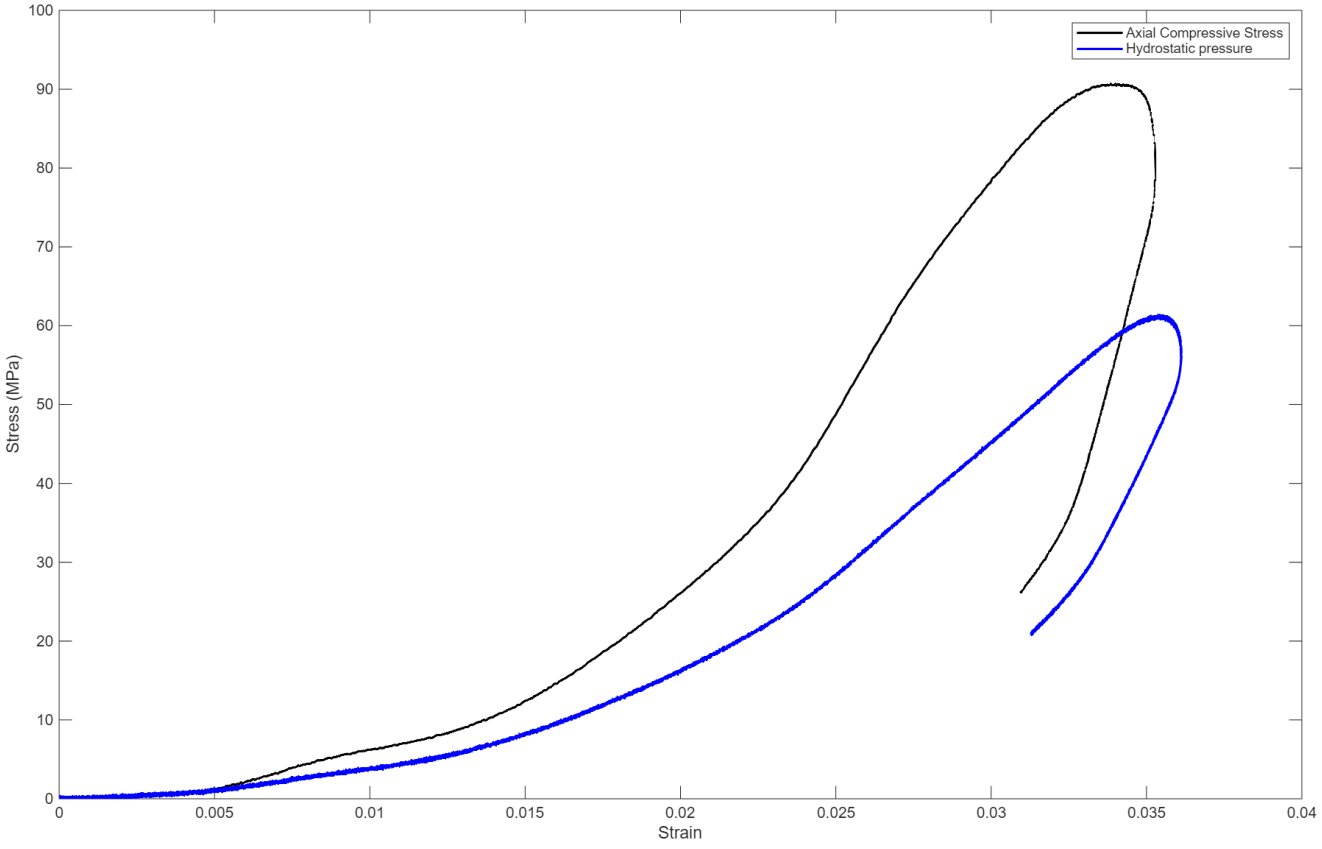

Fig. 3 Compressive engineering stress-strain and hydrostatic stress-volumetric strain relationships of composite IDOX/Estane under confinement loaded at strain rate 120 s^{-1}.

at ∼3.5% axial strain and 60 MPa hydrostatic stress at ∼3.5% of volumetric strain, followed by rapid post-peak softening associated recovery of the specimen.

Conclusion and Future Work

In this work, the confined high-strain-rate mechanical response of a surrogate high explosive was experimentally characterized using a split Hopkinson pressure bar under passive radial confinement. A registry marking technique was developed and implemented to preserve the spatial orientation of each specimen, enabling consistent alignment between pre-test characterization, dynamic loading, and post-test analysis. This approach provides a more realistic representation of the stress state experienced by confined granular energetic materials and establishes a reliable experimental framework for measuring coupled hydrostatic and deviatoric behavior at high strain rates.

Future work will focus on detailed post-mortem characterization of recovered specimens using high-resolution μCT. These measurements will enable quantification of damage evolution, void collapse, grain rearrangement, and interfacial debonding induced during dynamic loading. The resulting microstructural datasets will support the development and validation of microstructure-informed constitutive and computational models for surrogate and energetic granular composites under extreme loading conditions.

Acknowledgments We acknowledge the support of the Department of Energy, National Nuclear Security Administration, Predictive Science Academic Alliance Program (PSAAP) under Award Number DE-NA0003962. We also thank the support of NSF under 2219347 & 1726435. Lu also acknowledges the Louis A. Beecherl Jr. chair for additional support.

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