Shockwave dissipation by interface-dominated porous structures

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Shockwave interactions with heterogeneous, microscale features can result in energy localization. For example, in pressed explosives, these interactions lead to “hot spots” and are the means by which they initiate to detonation.\textsuperscript{1}\textsuperscript{,}4 It has been found experimentally that the critical spacing for constructive wavelet interactions on the timescale of detonation is a few \(x \approx 100 \mu \text{m}\).\textsuperscript{2}\textsuperscript{,}3 Conversely, an opposite, dissipative phenomenon could be induced in an inert material through the interaction of rarefaction (release) waves via an arrangement of free surfaces, impedance mismatches, or voids within a three-dimensional (3D) structure. Some shock-mitigating materials exploit porosity and layered structures to reduce the shock magnitude, yet these materials have lacked structural control and are largely developed via trial-and-error.\textsuperscript{1}\textsuperscript{,}2\textsuperscript{–}4\textsuperscript{,}42 Others have attempted to reduce the shockwave magnitude via energy-absorbing shock-driven reactions.\textsuperscript{1}\textsuperscript{,}4\textsuperscript{–}4\textsuperscript{,}42 However, there remains a need, and guiding principles, for structural materials, which have dimensional stability and tailorable mechanical properties, combined with shock or blast wave protective properties.

The advent of additive manufacturing (AM) has enabled topological control of structures at the micrometer scale, transforming the properties of polymers for a variety of applications. Examples include tailored mechanical responses, acoustic properties, and thermal properties. Porous polymer materials are a class of materials used for shock and blast mitigation, yet they frequently possess a lack of structural order and are largely developed and evaluated via trial-and-error. Here, we demonstrate control of shockwave dissipation through interface-dominated structures prepared by AM using 2-photon polymerization. A fractal structure with voids, or free surfaces, arranged less than 100 \(\mu \text{m}\) apart, allows for rarefaction interactions on the timescale of the shockwave loading. Simulations and dynamic x-ray phase contrast imaging experiments show that fractal structures with interfaces assembled within a “critical” volume reduce shockwave stress and wave velocity by over an order of magnitude within the first unit cell.
with a voxel scan speed of 10 mm/s. Each structure took 99 h to fabricate.

The structures were initially imaged in the laboratory using a Carl Zeiss X-ray Microscopy, Inc. (Pleasanton, CA) Versa 520 microcomputed tomography (CT) instrument. The samples were positioned on the glass substrate during CT imaging. Due to the cone-beam geometry of the instrument, and the small size of the sample on top of the large glass plate (1.7 mm and 1 cm, respectively), the substrate was mounted on a small double goniometer to ensure that the substrate was level to the instrument. Some artifacts are still seen in the images, namely, the noise in the image at the bottom of the sample in Fig. 1. Figure 1(a) shows an x-ray radiograph of a third-order Menger structure with dimensions of \(1.7 \times 1.7 \times 1.7 \text{ mm}^3\). At this scale, the void dimensions are \(x = 0.560 \text{ mm}, 0.180 \text{ mm}, \) and \(0.063 \text{ mm} \) (per side). The 3D rendering is shown in Fig. 1(b).

Gas gun-driven plate impact experiments were diagnosed with in situ, time-resolved x-ray phase contrast imaging (PCI) at the Dynamic Compression Sector (DCS) of the Advanced Photon Source (Argonne, IL) for interrogating real-time shockwave propagation and localization phenomena as described previously.\(^{46–48}\) The 8-frame x-ray PCI system integrates dynamic imagers with 2 \(\mu\text{m}–3 \mu\text{m} \) resolution, and frames timed to each bunch of the 24-bunch mode of the advanced photon source (APS) (153.4 ns). Briefly, a 12.7 mm bore single stage light gas gun launches projectiles containing 6061-T6 aluminum impactors into instrumented targets that are aligned to both the gun barrel and pink x-ray beam (\(E = 25.0 \text{ keV}, \lambda = 0.05 \text{ nm})\). The phase contrast images were corrected for detector efficiency and background signal and analyzed using the Image J software suite. The AM structures were affixed to the rear surface of 6061-T6 Al baseplates and sandwiched by an aluminum-mirrored polymethyl methacrylate (PMMA) rear window for measuring the interface particle velocity of the transmitted shockwave using photonic Doppler velocimetry (PDV, AC Photonics).\(^{42}\) Gas gun-driven plate impact imparted a supported shockwave into the AM samples. Three collimated PDV probes were fielded to measure the projectile velocity, and the times of shock entry and exit in the sample. A protruding piezoelectric impact pin (Dynasen, Inc.) was used to synchronize the impact event, the PDV diagnostics, incident x-ray bunch pulse, and the detectors. We previously reported the application of this approach with more detail of the experimental setup.\(^{46,47,53}\) Impact experiments were performed at \(u_0 \sim 0.3 \text{ km/s}\).

The response of the third-order Menger structure to shockwave loading is shown in the x-ray PCI images in Fig. 2, timed sequentially to the bunch structure of the APS (\(\Delta t = 153.4 \text{ ns}\)). The first image at 6.648 \(\mu\text{s}\) (arbitrary time from pin trigger) is the static, pre-shock x-ray image, followed by 7 dynamic frames. The shockwave localization and compaction behavior is found to be quite different than stochastic polymer foams and polymer lattice structures that our team has studied previously.\(^{46–48}\) Shockwave coupling to the Menger structure results in viscoplastic deformation of the cells, and sequential compaction of the layers bends the shock front, with lateral displacement of materials normal to the shock propagation direction. This behavior is attributed to the properties of the acrylic polymer (ductility and strength) at these strain rates \((10^3 \text{s}^{-1})\). The initially cubic voids plastically deform into diamond-shaped voids as the shock drives the upstream free surface into the void volume. We find that the particle velocity and shock stress are reduced by an order of magnitude over 1 mm of propagation distance in the structure, and by over 10-fold compared to what would be expected in a solid structure of 2PP acrylate. The transmitted particle velocity at the PMMA window, \(u_{\text{p,int}} = 0.057 \text{ mm/}\mu\text{s}\) (see supplementary material Fig. 1) is consistent with transmitted pressure \(P_{\text{avg}} \sim 0.04 \text{ GPa}\). The expected shock stress in fully dense acrylate at this input condition is \(-0.65 \text{ GPa},\) based on the measured Hugoniot for the 2PP-acrylate.

Simulations of the shockwave experiments were performed using the Finite Element Method (FEM) simulation code ABAQUS with a user defined material model to provide details of dissipation through the structures. In the model, the stress material response is obtained from a partitioning of deviatoric stress \(s_{ij}\) and pressure \(p\),

\[
\sigma_{ij} = -p + s_{ij},
\]

and pressure

\[
p = \frac{p_0 c_0^2 \eta}{(1 - s_\eta)} \left(1 - \frac{\Gamma_\eta}{2}\right) e,
\]

where \(\eta = 1 - \rho_0/\rho\), \(\Gamma\) is the Grüneisen parameter, \(e\) is the internal energy, \(c_0\) is the intercept of the linear Rankine–Hugoniot fit to experimental Hugoniot data in the shock velocity \((U_s)\) vs particle velocity \((u_p)\) plane, and \(s\) is the slope of the Rankine–Hugoniot fit. \(c_0\) and \(s\) are related to the ambient pressure isentropic bulk modulus and its pressure derivative, respectively. In (1), the pressure \(p\) was obtained from the Mie–Grüneisen \(U_s - u_p\) equation of state (EOS). Material parameters came from the study of Dattelbaum.
FIG. 2. Pre-shock (static, 6.648 μs) and 7 dynamic frames from x-ray phase contrast imaging of a third order Menger structure under shockwave loading (Shot 19-2-018). The times shown are from pin trigger (arbitrary) and are timed to the bunch structure of the 24-bunch mode of the Advanced Photon Source (Δt = 153.4 ns). The impact velocity was \( u_0 \approx 0.318 \text{ km/s} \), with the shockwave traveling from right-to-left in the images. The rear PMMA window can be observed on the left-hand side of the images. Photonic Doppler velocimetry was used to measure the shockwave breakout at the rear (free) surface of the Al baseplate, and foam/PMMA interface (see the supplementary material).

et al.,\textsuperscript{24} in which the Rankine–Hugoniot fit to the shock adiabat for the 2PP-acrylic is \( U_s = 1.22 + 2.43u_p \) (\( \Gamma = 1.5 \), estimated). The deviatoric response, \( \dot{s}_{ij} \), was modeled using a viscoplastic material model:\textsuperscript{55}

\[
\dot{s}_{ij} = 2\mu\left(\dot{e}_{ij} - \dot{e}_{ij}^v - \dot{e}_{ij}^p\right),
\]

where \( s \) is an objective rate stress rate, \( \mu \) is the shear modulus, \( \dot{e}_{ij} \) is the deviatoric strain rate, and \( \dot{e}_{ij}^v \) and \( \dot{e}_{ij}^p \) represent the deviatoric viscoelastic and plastic rates. In the numerical simulations, a comparison of three orders of Menger structures (M01, M02, and M03) was investigated, with the “order” of the structure corresponding to the fractal dimension of voids.

The Menger structures were subjected to a flyer impact with velocity \( u_0 \approx 0.318 \text{ km/s} \) in ABAQUS, and the problem was analyzed for a duration of 2 μs. To compare the numerical results vs experiment, an arbitrary position “A” was designated as the lower right-hand material element on the corner of Menger structure at the baseplate. Material displacement in the shock (Z) and lateral (Y) directions was determined from both the experimental PCI data and the ABAQUS simulations. The results are shown in Fig. 3. The slope \( \Delta Z_A/\Delta t = 0.318 \text{ mm/μs} \), which approximates the velocity of the flyer, and is consistent with the free surface velocity of the baseplate (and in-material particle velocity in the shock direction). The position \( Y_A \) is the lateral displacement of point A. At early times, there is an excellent (<0.05 mm/μs) difference between the experiment and simulation. After \( t > 1.1 \text{ μs} \), there is an increase in difference between the numerical results and experimental results, which is due to lateral material ejection at high strains captured in the PCI images. Material displacement vs time is dominated by compression in the shock direction.

FIG. 3. Material displacement in the shock (z) and lateral (y) directions for a material element “A” at the lower right-hand corner of the Menger structure for the experiment shown in Fig. 2, as a function of time.
For each structure, the dissipation energy was determined from

\[ E_{vp} = \int_0^T \dot{\varepsilon}_{vp} dt = \int_0^T \int_V \left( \dot{e}_{ij}^v + \dot{e}_{ij}^p \right) dV dt, \]  

where \( V \) represents the volume of the structure, and \( T^* \) represents the total time. The temperature \( T \) was calculated from Ref. 55 and Eq. (5),

\[ \dot{T} = \frac{E_{vp}}{c_v} - \rho T \dot{e}_0. \]  

Figure 4(a) shows the initial first, second, and third-order Menger structures.

Upon flyer impact, energy is imparted to the Menger structure, which is a sum of the kinetic (\( E_K \)) and internal (\( E_I \)) energies. Denoting by \( \Delta E_T \), the total energy transmitted by the flyer to the structure is

\[ \Delta E_T = \Delta E_K + \Delta E_I = \Delta E_K + \Delta E_e + E_{vp}, \]  

where \( \Delta E_K \) represents the increase in kinetic energy, and \( \Delta E_I \) is the internal energy, which is equal to the sum of the elastic energy \( \Delta E_e \) and the energy dissipated as the viscoplastic work \( \Delta E_{vp} \). The energy partition can be written as fractions of the total energy: \( \phi_k = \Delta E_K / \Delta E_T \), \( \phi_e = \Delta E_e / \Delta E_T \) and \( \phi_{vp} = E_{vp} / \Delta E_T \), and \( \phi_k + \phi_e + \phi_{vp} = 1 \). Figure 5 shows the evolution of the energy partition fractions as a function of time for (from left to right) M01, M02, and M03.

From Fig. 5, one observes that \( \phi_e \) becomes an approximately constant value over time, but the time to reach this value becomes shorter as the order of Menger increases. This can be correlated with a decrease in void spacing, allowing rarefaction waves to interact.
between the void surfaces on a faster timescale. As $\phi = const$, it follows that the variation in energy partition is between the kinetic and dissipation energy both evolving in the opposite phase in time as shown in Fig. 5. This dissipation energy enters in the temperature calculation in the material model. Numerical results have shown that this yields temperature localization around the voids, as shown in Fig. 4 and supplementary material Fig. 4, with a temperature rise of $\Delta T = +170$ K. The localization indicates a higher increase locally as the order of Menger structure increases due to plastic deformation of the voids in the structure.

The second principal effect that shockwave coupling to fractal structures will have is the complex wave interactions arising from the shock and rarefaction waves associated with the arrangement of voids and free surfaces. Interactions between rarefaction waves originating from the free surfaces have a characteristic timescale of $t \sim L/2c_{l}$, where $L$ is the distance between free surfaces and $c_{l}$ is the sound velocity at pressure on the principal isentrope and is the rarefaction head velocity. This is similar to the constructive interference that occurs for deflagration wavelets in the hot spot-driven initiation of explosives. At the input shock condition to the 2PP-acrylate polymer, the sound velocity on the principal isentrope is $c_{l} \approx 2.30 \text{ mm/µs}$. The distance between the free surfaces of the voids, $L$, is for $M_{1} = 1.12 \text{ mm}, M_{2} = 0.36 \text{ mm},$ and $M_{3} = 0.126 \text{ mm}$. Only in the third-order structure does the rarefaction interaction timescale approach that of the incident shock, resulting in reduction in the shock stress through rarefaction wave interactions.

In summary, “interface-dominated structures,” such as fractal structures, show promise for dissipating shockwave energy through two effects: viscoplastic deformation and associated energy conversion to heat, and edge-release (rarefaction) wave interactions on relevant timescales to shockwave propagation. In the first case, the analysis has shown high localization of the dissipation energy at the interfaces yielding to a high increase in temperature in these regions. The degree of localization increases with fractal order. In the latter, the sound velocity at pressure and compressibility along the Hugoniot and principal isentrope dictate the shock and rarefaction wave speeds that result in a “ringing-down” of the shock stress in the structure. Simulations and dynamic x-ray PCI experiments have shown that fractal structures with interfaces assembled within a “critical” volume reduce shockwave stress and wave velocity by over an order of magnitude within the first unit cell.

The supplementary material provides additional details of the ABAQUS Explicit simulations, experimental velocimetry and PCI results, and plots of dissipation energy vs time for Menger structures.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Computed tomography used a 4× objective, and 1.5 s exposure time over 3001 images (60 keV, 5 W source, 2.7 μm pixel size).