Attenuation of shock waves propagating through nano-structured porous materials

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(Received 4 January 2013; accepted 21 May 2013; published online 10 July 2013)

Porous materials have long been known to be effective in energy absorption and shock wave attenuation. These properties make them attractive in blast mitigation strategies. Nano-structured materials have an even greater potential for blast mitigation because of their high surface-to-volume ratio, a geometric parameter which substantially attenuates shock wave propagation. A molecular dynamics approach was used to explore the effects of this remarkable property on the behavior of traveling shocks impacting on solid materials. The computational setup included a moving piston, a gas region and a target solid wall with and without a porous structure. The gas and porous solid were modeled by Lennard-Jones-like and effective atom potentials, respectively. The shock wave is resolved in space and time and its reflection from a solid wall is gradual, due to the wave’s finite thickness, and entails a self-interaction as the reflected wave travels through the incoming incident wave. Cases investigated include a free standing porous structure, a porous structure attached to a wall and porous structures with graded porosity. The effects of pore shape and orientation have been also documented. The results indicate that placing a nano-porous material layer in front of the target wall reduced the stress magnitude and the energy deposited inside the solid by about 30 percent, while at the same time substantially decreasing the loading rate. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4811720]

I. INTRODUCTION

Lightweight, energy absorbing materials are of great interest in numerous scientific and engineering applications particularly where vibration damping or impact energy absorption and protection are important. Incorporation of emerging nano-technologies in developing new materials with enhanced properties and devices that operate at length scales where classical Newtonian physics breaks down is necessary to overcome the challenges involved in establishing novel solutions to meet specific needs. Structured nano materials, because of their high surface-to-volume ratio, offer an unprecedented platform to manipulate shock or blast waves propagating through them and mitigate their effect by dissipation or phase cancellation. The thermomechanical behavior of such materials under the effects of large dynamical extremes, such as those resulting from shock impacts, requires knowledge of interactions at the atomic, molecular, and microstructural levels. In the present work we extend the molecular dynamics (MD) methodology described in Ref. 1 to evaluate the interaction of traveling shock waves with nano porous materials in different configurations and for various geometrical attributes such as porosity, graded functionality, and orientation.

MD has been used in the past few decades to investigate the behavior of flows in the presence of a shockwave. Tsai et al.2 studied the propagation of a planar shock in a dense Lennard-Jones fluid. Holian et al.3 simulated a dense-fluid shock wave with 4800 particles and found differences...
in the predictions of mean temperature density and velocity to be relatively small when compared with the Navier-Stokes continuum mechanics, provided non-equilibrium constitutive relations were used. Holian further demonstrated that the constitutive model of Navier-Stokes hydrodynamics was accurate even at the small time and distance scales of MD. In all of these continuum computations using the Navier-Stokes equations, the gradients across the shock were approximated by hyperbolic tangent distributions. Woo et al. have simulated piston-driven shock wave in hard sphere gas at Mach 1.5, 3, and 10. Hoover simulated the structure of a moving shock wave front in a dense Lennard-Jones fluid, and found a good agreement with the solutions of the Navier-Stokes equation for strong shocks. Schlamp et al. simulated shock waves in dense nitrogen and resolved the steady state shock structure with 0.25 Å resolution, corresponding to 0.1 mean–free paths or 1/30th of the shock thickness. Wave propagation in nonlinear granular columns was studied by Sinkovits and Sen who used mesoscale resolution and MD-like concepts that involved a potential based on repulsive forces between grains consisting of many atoms.

At the continuum level, a shock is considered a discontinuity with unknown properties and its reflection over a flat surface occurs at the same time as its impact, since the shock thickness is not resolved. Typically, the process of reflection has a time scale of 0.25 ns for shock thicknesses and propagation velocities of 100 nm and 400 m/s, respectively. These requirements in temporal and spatial resolutions for this interaction necessitate the use of atomistic level computer simulations. The novelty of the present work is in the nanoscale resolution of the mutual interaction between a shock wave and structured materials which includes, for the first time, a simultaneous and integrated/coupled treatment of multiple wave phenomena in both gas and solid phases. The present contribution complements our macroscopic experimental and computational studies with periodic composite structures and functionally graded materials subjected to shock loading, and has the potential to bridge the gap between atomistic and meso-scale modeling. Previous work describes shock interactions only at a much coarser level by averaging over atomic variables, and can only address this issue by trial and error.

The interaction of shock waves with gas-solid mixtures at the macroscopic level has attracted the attention of many researchers and a substantial amount of experimental theoretical and computational work has been reported. It is reasonably well documented that shock waves propagating in foams or porous materials are attenuated and such accurately controllable shock attenuations are widely used in various engineering and industrial applications. Single and multi-phase approaches have been developed and tested to model these phenomena based on microscopic conservation laws of mass, momentum, and energy from which macroscopic evolution equations (ordinary and partial differential equations) are derived, complemented by appropriate closures. The first fundamental study on the subject is that of Biot on compression wave propagation by using poro-mechanics.

Microscopic representations of phase balance equations within the framework of the theory of mixtures followed Biot’s pioneering work, but applying these concepts to nonlinear waves led to poor results. A more accurate representation of the momentum and energy processes at the internal surfaces of the porous medium was introduced by including the nonlinear drag law known as Forchheimer term in the model of Ref. During shock wave loading of a saturated porous material, the initial step-wise perturbation is split into two parts: the first wave in which pore fluid and porous material are compressed simultaneously, i.e., the solid and fluid particles have in phase motion, and a second wave in which the pore fluid is compressed again, while the porous material relaxes, i.e., the two phases have out of phase motion. Grinten and Levy et al. found that the compaction wave broadens as it travels through porous specimens and becomes dispersed.

Although waves moving through porous materials are attenuated, substantial amplification can occur when the material is placed in the vicinity or in contact with a backing plate. If porous materials are used as barriers to protect structures, measurement of the total stress transmitted to the backing wall is more important than the pressure in the fluid phase. Such measurements have been reported in cases of polymeric (flexible) foams and granular materials under shock compaction. Yasuhara et al. investigated experimentally the effect of porosity and the internal structure on the total stress at the back wall. For all foams tested in these experiments the maximum transient total stress at the back wall is larger than the pressure behind the reflected shock off a rigid wall.
It was also observed that there is a delay time for the total stress rise compared to the rise of the pressure upon the reflection of the incident shock wave off a rigid wall suggesting that the stress wave transmitting through the foam decelerates as it moves within the foam. Britan and Ben-Dor and Ben-Dor et al. argue that the filtration process causes energy loss in the transmitted stress wave in the granular material, thus reducing the stress value.

The recent work by Kazemi-Kamyab et al. has shown that by carefully selecting a porous material and its size it is possible to cancel out the contributions from the gas and solid phases and therefore avoid the stress wave overshot inside the back wall. The time-dependent signals were decomposed into two components, one with low frequency content which is argued that it is associated with Biot’s slow wave and one with high frequency contributions which corresponds to the fast wave propagation. It has been also argued that this decomposition can differentiate the effects of gas pressure in the pores from the stress in the matrix of the porous medium.

II. MOLECULAR DYNAMICS METHOD

The computations employ standard classical molecular dynamics (MD) techniques, which can readily account for the effects of pressure and temperature variation and the deformation and evolution of the solid structure. As indicated in Fig. 1, we formulate the interaction of a shock with a solid in direct imitation of a laboratory experiment by equilibrating a system consisting of a gas placed in contact with a porous solid, sandwiched between a movable rigid piston and a fixed holding wall, and then moving the piston sufficiently rapidly inwards to create a shock which impinges on the solid. During the latter process, in addition to monitoring molecular positions and velocities we compute local time-dependent averages of the temperature and stress fields in order to connect the results to the conventional continuum description of shock dynamics.

A. Interactions

The behavior of the gas and the target are the focus of this calculation and these materials require realistic interaction potentials, while the piston and holding wall play only a secondary role in the process and a simpler model suffices for their material properties. The gas molecules and the atoms in the piston and holding wall interact via a basic, two-body, Short Range Attractive potential (SHRAT) of Lennard-Jones form. The SHRAT potential takes the form

$$U_{\text{SHRAT}}(r) = \begin{cases} \frac{512}{27} \phi_0 \left(1 - \frac{r}{\psi}\right)^3, & r \leq 1.5 \psi \\ 0, & r > 1.5 \psi \end{cases} \tag{1}$$

where $r$ is the separation between two atoms, $\phi_0$ is the depth of the potential well and $\psi$ roughly corresponds to the atomic diameter, and also controls the cutoff distance. This potential is similar in shape to a standard Lennard-Jones function, but is smoother, since its first and second derivatives vanish at the cutoff, and somewhat faster in computation since it involves only positive powers of $r$.

Our principal motivation for choosing it, however, is to allow us check some of our intermediate results against earlier simulations of thermophysical properties by Hess and Kroger. In addition...
to the SHRAT interaction, the piston and holding-wall atoms are tethered to their lattice location
with elastic springs, so as to provide rigidity.

The solid particles in the target interact with each other with a realistic potential originating
in a widely-used approximation for metals such as nickel, the Generic Embedded Atom Method
(GEAM). This potential is the sum of two contributions: a conventional binary interaction term
with a two-body interaction potential \( U \) and a term stemming from an embedding functional \( \Theta \),
which models the effect of the electronic “glue” between atoms

\[
U = \lambda \left[ \sum_{i=1}^{N} \Theta \left( \rho_{i}^{emb} \right) + \sum_{i=1}^{N} \sum_{j \neq i}^{N} U \left( r_{ij} \right) \right],
\]

where \( \lambda \) controls the overall strength of the interaction. The binary interaction term for the solid
atoms is a slightly different SHRAT potential

\[
U \left( r \right) = \phi_{0} \psi^{-4} \left[ 3 \left( r_{cut} - r \right) \right] - \left( r_{cut} - r_{min} \right) \left( r_{cut} - r \right)^{3}],
\]

where \( r_{ij} \) is the distance between atoms \( i \) and \( j \), \( r_{cut} = 1.6 \psi \) and \( r_{min} = 2^{1/6} \psi \). The embedding
functional \( \Theta \) is a nonlinear function of the (local) embedding densities \( \rho_{i}^{emb} \) of atoms \( i \), which in
turn are constructed from the distances to the surrounding atoms and a weighting function \( w(r) \)

\[
\rho_{i}^{emb} = \sum_{j=1}^{N} \sum_{i \neq j}^{N} \left( w \left( r_{ij} \right) + w \left( 0 \right) \right)
\]

with

\[
w \left( r \right) = w_{0} \left( 1 + 3 \frac{r}{r_{cut}} \right) \left( 1 - \frac{r}{r_{cut}} \right)^{3}.
\]

The embedding potential functional itself is a polynomial of the form

\[
\Theta \left( \rho_{i}^{emb} \right) = \phi_{0} \sum_{k=2,4,6} \alpha_{k} \left[ \left( \rho_{i}^{emb} - \rho_{i}^{des} \right)^{k} - \left( w_{0} - \rho_{i}^{des} \right)^{k} \right] r^{-3k},
\]

where \( \rho_{i}^{des} = \psi^{-3} = N/V \) is the desired embedding number density and \( \alpha_{k} \) are embedding strengths
which are part of the parametrization of the model. Odd terms in the sum are excluded since their
contribution would be always repulsive in nature; the linear term (\( k = 1 \)) could be adsorbed in
a modified pair potential \( U \). As in the SHRAT potential, we use a polynomial function in the embedding
functional as a computationally less expensive alternative to the standard logarithmic form.

The GEAM potential involves both local two-body terms and a collective “embedding” term
based on a sum over neighbor atoms within a cutoff. The potential was developed for a fully periodic
material where all sites are equivalent, and the potential maintains rigidity of the solid. In the present
work, the geometry of this problem requires a finite-thickness solid slab, which breaks periodicity
in the Y-direction, so that there are no neighbor atoms at the two edges of the target. Without
modification the target would fall apart due to insufficient binding, and a simple remedy is to add
layers of “ghost” atoms to either side – the ghost and holding walls – which provide a uniform
embedding density and maintain the target’s rigidity. The role of the ghost atoms is to insure that
each solid atom, including those at the solid-vapor interface, has on average the same number of
interacting neighbor atoms and therefore relatively uniform values for the two-body potential and
the embedding density function. The ghosts interact only with the “physical” solid atoms and not the
vapor molecules, and provide both the incompletely-periodic solid and the porous solid structures
with their necessary rigidity. The holding wall at the far edge of the simulation box has two roles –
first to prevent the target from simply sliding downstream when the shock reaches it and second, as
with the ghost particles, to appear in the embedding density for the physical solid atoms at the far
side of the wall to maintain rigidity.

The parameters used in the present work, in which a nickel solid is simulated, are shown in
Table I. Values for Ag and Cu are also given for comparison.
TABLE I. GEAM and physical parameters for various metals.

<table>
<thead>
<tr>
<th>Material</th>
<th>rcut</th>
<th>rmin/1.6</th>
<th>α</th>
<th>Mass/atom (kg)</th>
<th>ψw (m)</th>
<th>φ0w (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>1.010</td>
<td>1.00</td>
<td>0.42</td>
<td>1.06 × 10^{-25}</td>
<td>2.27 × 10^{-10}</td>
<td>5.62 × 10^{-21}</td>
</tr>
<tr>
<td>Ag</td>
<td>1.006</td>
<td>1.00</td>
<td>0.70</td>
<td>1.790 × 10^{-25}</td>
<td>2.58 × 10^{-10}</td>
<td>4.74 × 10^{-21}</td>
</tr>
<tr>
<td>Ni</td>
<td>1.017</td>
<td>1.02</td>
<td>0.20</td>
<td>9.75 × 10^{-26}</td>
<td>2.28 × 10^{-10}</td>
<td>7.15 × 10^{-21}</td>
</tr>
</tbody>
</table>

B. Reference values

The numerical calculations are carried out using dimensionless variables based on the energy scale \( \phi_0w \) and the length scale \( \psi_w \) of the wall interactions and the atomic mass of a wall atom \( m_w \). Note that these are also the parameters of the gas. The relevant scales for the quantities discussed in the results below, along with their numerical values for nickel, are given in Table II.

C. The nano shock tube model geometry

The physical computational domain is shown in Fig. 1: a long channel of square cross section which, reading from left to right, contains a piston, a gas region, a target solid wall, and a holding wall. The size of the domain is \( L_x \times L_y \times L_z = 29 \psi_w \times 133.7 \psi_w \times 29 \psi_w \), where \( \psi_w \) is the characteristic length in the gas potential, roughly an atomic diameter – a few Angstroms. The piston and the holding wall are composed of two layers of face-centered cubic (fcc) lattice with thickness \( a = 3.22 \psi_w \) and 2592 nickel atoms. The target solid is placed at the right end of the domain, and consists of a thicker slab of 12 960 nickel atoms occupying an axial length of 16.1 \( \psi_w \). The gap between the piston and target (of length \( L_y = 107.93 \psi_w \)) is filled with 2708 argon atoms. For computational purposes, a “ghost wall” identical to the holding wall is placed to the left of the target.

D. Solution method and boundary conditions

The atoms move according to Newton equations of motion which are integrated in time using a 5th order predictor corrector algorithm. The time step is set to 0.005 in dimensionless units, or 10 fs.

Periodic boundary conditions are used in the lateral directions but were abandoned in the normal direction since the atomistic is symmetric in the lateral directions only. The Lorentz-Berthelot mixing rules are used for estimating intermolecular potential parameters between pairs of non-identical molecules. For the interaction of hetero-atomic pairs, the effective values of \( \psi \) and \( \phi_0 \) are calculated from those for the homo-atomic pairs using the arithmetic mean for \( \psi \), \( \psi_{ab} = 0.5(\psi_a + \psi_b) \) and the geometric mean for \( \phi_0 \), \( \phi_{0ab} = \sqrt{\phi_{0a}\phi_{0b}} \). Length and energy scales for the solid particles are shown in Table I, while length and energy scales for argon are \( 3.405 \times 10^{-10} m \) and \( 1.65 \times 10^{-21} J \), respectively.

Local quantities such as density, velocity, temperature and stress are computed during the simulations by subdividing the computation domain into 2D cells or “sampling bins” in the Y-X plane, which fill the computational domain without gaps and overlaps (see Fig. 2). Each cell has a

TABLE II. Reference values for dimensionless derived quantities.

<table>
<thead>
<tr>
<th>Derived quantity</th>
<th>Reference quantity</th>
<th>Reference value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>( \psi_w (m_w/\phi_0w)^{1/2} )</td>
<td>( 8.42 \times 10^{-13} ) s</td>
</tr>
<tr>
<td>Density</td>
<td>( m_w/\psi_w^3 )</td>
<td>( 8.23 \times 10^{13} ) kg/m^3</td>
</tr>
<tr>
<td>Temperature</td>
<td>( \phi_0w/k_B )</td>
<td>( 5.18 \times 10^{12} ) K</td>
</tr>
<tr>
<td>Pressure</td>
<td>( \phi_0w/\psi_w^2 )</td>
<td>( 6.03 \times 10^{18} ) Pa</td>
</tr>
<tr>
<td>Velocity</td>
<td>( \sqrt{\phi_0w/m_w} )</td>
<td>( 271 ) m/s</td>
</tr>
<tr>
<td>Heat Flux</td>
<td>( \phi_0w/\psi_w^3 m_w^{-1/2} )</td>
<td>( 1.63 \times 10^{11} ) W/m^2</td>
</tr>
</tbody>
</table>
size of $1.61 \psi_w$ or one layer of a cubic face centered lattice. In each cell, one accumulates the value of the field of interest, given by a local function of atomic positions and velocities, $r$ some time interval and then computes the average. One-dimensional profiles are computed by averaging over the cells in transverse-direction, reducing the 2D cell configuration to a one-dimensional array of vertical slabs. Additional information can be found in Ref. 36.

E. Equilibration

The atoms are initially placed at exact face centered cubic lattice sites, and the system is first allowed to evolve an equilibrium state at (dimensionless) temperature $T = 1.0$, over 50 time units, at which point the solid atoms have constant mean-square fluctuations about their lattice sites and the gas molecules fill their region randomly and uniformly on average.

F. Shock wave formation and propagation

After equilibration, the piston was set into motion by giving its atoms an extra prescribed velocity to the right, which forces the gas to compress and move in that direction. When this translational velocity exceeds the sound speed a shock wave is formed, which moves towards and eventually impacts the solid wall. The motion of the piston is then stopped but the shock continues to move through the solid, and reflects at the gas-target and target-holding wall boundaries. Properties of both solid and gas phase regions were averaged locally over the cell size every 0.2 time units.

Results are presented below for a flow with compression ratio $\rho_0/\rho_1 = 0.38$, a corresponding piston velocity $u_p = 4.0(\phi_0/\rho_0)^{1/2}$ and a shock wave velocity $u_s = 6.452(\phi_0/\rho_0)^{1/2}$. Under these initial conditions Argon remains in the gas regime (Holian et al.7). The shock thickness evaluated as $\Lambda = (\rho_1 - \rho_0)(\partial \rho / \partial \psi)|_{\text{max}}$ is $\Lambda = 6.614 \psi_w$; the volumetric strain in the shock defined as $\xi = \rho_0/\rho_1 - 1 = -u_p/u_s$ is $\xi = -0.62$ and the volumetric strain rate defined as $\dot{\xi} = \xi u_s / \Lambda = -u_p / \Lambda$ is $\dot{\xi} = -0.605 s^{-1}$.

G. Cases investigated

A reference case was simulated first in which a moving shock impacted a uniform elastic wall. This case, designated as Case 0, provided bench-mark data used to compare to the cases involving porous material structures. In Case 1, a free-standing porous structure consisting of straight cylindrical poles was placed at some distance from the end wall target, as shown in Figures 3(a) and 3(b). Poles are placed first parallel to the direction of the shock wave propagation as depicted in Figure 3(a). The shock wave is formed by the piston motion that will propagate in the gas channel and will impact the front section of the freestanding poles. Part of the shock will be reflected and part will continue propagating into the space between the poles and eventually will exit the porous structure and will continue moving towards the end section of the gas channel where, finally, it will impact the holding wall and be reflected back into the gas channel. In a second configuration, the porous structure was turned 90° so that the poles are perpendicular to the flow direction as shown Figure 3(b). The porous length is chosen so that it is comparable to that of previous parallel porous cases. Dimensions of the gas channel remained unchanged.
Case 2 a porous structure consisting of straight poles is attached to a solid particle wall as shown in Figure 3(c). Figure 3(d) shows the geometry of Case 3a in which graded porosity was setup by linearly varying the cross section of the conical poles. Two more additional 7 cases with graded porosity were investigated with mixed pole geometry: the yellow poles shown in Figure 3(e) have been replaced with straight poles of constant porosity (Case 3.2) or with conical poles of increasing porosity (Case 3.3) as shown in Figure 3(f). In all cases, the average porosity was 80% and initial gas density was set to $0.0298 \Phi_w^{-3}$.

In each case, after equilibration the piston was translated towards the target wall at constant speed 4.0. Once the shock reaches the solid wall, the piston was stopped. Table III provides a summary of the various investigated cases.

III. REFERENCE FLOW, CASE 0: UNIFORM SOLID WALL

Figure 4(a) shows the density contours along the length of the gas channel at different times as the piston moves. In this x-t diagram, the induced flow behind the shock is confined between the two edges of the graph representing the piston path and the travelling shock front trajectory. The two edges diverge because of their different propagation velocities. The shock and the induced flow behind appear to be developing up to a distance of $50 \Psi_w$, where the density reaches a constant value of $0.08 m_w/\Psi_w^3$. Small fluctuations in density are evident upstream and before the arrival of the shock front, which are remnants of the equilibration process. An expanded view of the region...
TABLE III. Summary of investigated cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Porosity</th>
<th>Pole geometry description</th>
<th>Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100%</td>
<td>No poles</td>
<td>Solid wall</td>
</tr>
<tr>
<td>1</td>
<td>96%, 80%, 66%</td>
<td>Straight poles parallel and normal to shock propagation direction</td>
<td>Free-standing porous structure at a distance off the solid wall</td>
</tr>
<tr>
<td>2.0</td>
<td>80%</td>
<td>Straight poles orthogonal to shock direction</td>
<td>Porous structure attached to solid wall</td>
</tr>
<tr>
<td>3.1</td>
<td>80%</td>
<td>Graded increasing thickness conical poles</td>
<td>Porous structure attached to solid wall</td>
</tr>
<tr>
<td>3.2</td>
<td>80%</td>
<td>Graded conical poles and straight poles</td>
<td>Porous structure attached to solid wall</td>
</tr>
<tr>
<td>3.3</td>
<td>80%</td>
<td>Graded increasing/decreasing thickness conical poles</td>
<td>Porous structure attached to solid wall</td>
</tr>
</tbody>
</table>

of interest that includes the area between location $Y = 80\psi_w$ and the wall, during times $t = 14$ through 22.5$t_r$, where $t_r$ is the reference time $t_r = \psi_w(m_w/\phi_{0w})^{1/2}$ is shown in Figure 4(b). The incident shock impacts the end wall (the target) at about $t = 16t_r$, and it is subsequently reflected and moves in the opposite direction towards the piston. The incoming shock has a finite thickness and therefore its reflection takes place gradually. Both the reflected part of the shock and the not-yet-reflected part of the incident shock coexist, and as a result, the reflected shock interacts face-on with the non-reflected part of the incident shock wave. This is the major difference between the present atomistic calculations and macroscopic approaches where the shock reflects instantly from a solid surface. In addition, there is a substantial energy exchange between the flow and the solid wall during the reflection, which further complicates the process of reflection. The region very close to the wall where the interaction between the incident and reflected wave and the wall occurs is called the strong interaction zone (SIZ) in the present context. The result of this gradual reflection and the interaction of the shock with itself is an overshoot of the values of density and pressure by 20%–25% above the values associated with the flow after the end of the reflection has been observed in the SIZ. The thickness of the shock is about 10 $\psi_w$ and the extent of the SIZ with the intense interaction of the shock with itself is about half its thickness. Just before the reflection starts, the maximum density observed behind the incident shock is $0.08m_w/\psi_w^3$, and it increases to a maximum value of $0.185m_w/\psi_w^3$, more than twice that of the shocked gas. This value is associated with the processes within the SIZ. As the shock reflection is completed, the length of the SIZ is diminishing and a drop in gas density to $0.15m_w/\psi_w^3$ is observed in the region next to the solid-phase wall.

As shown in Figure 4(c), the pressure contours in the region of interest of the gas channel exhibit a behavior similar to that of the density. The pressure ratio across the incoming shock wave is about 10 and about 5 across the reflected shock. According to classical macroscopic shock tube theory, the corresponding pressure ratio in the case of a rigid wall reflection, $P_3/P_2$, is more than 33 for the same pressure ratio across the incoming shock of 10. This comparison clearly demonstrates the second quantitative difference between the present case with an elastic end wall and the classical shock reflection off a rigid body planar surface.

Figure 4(d) shows the temperature contours in the region of interest close to the end wall. The reflection of the incident shock at the end wall is associated with a considerable increase in temperature and a temperature ratio of about 4 across the incoming shock wave is observed; however, across the reflected shock the temperature is about 8 times greater than that of the unshocked gas. At the solid wall, the shock wave is partially reflected and partially transmitted into the solid phase with energy being exchanged, so that part of the shock wave energy is deposited back into the gas channel and the remaining part is exchanged with the solid molecules. The transmitted shock starts propagating inside the solid structure till it reaches the holding wall. Unlike the macroscopic behavior, the gas temperature behind the reflected shock is not constant at different times. Initially the temperature is high, and subsequently decreases due to the energy exchange with the solid wall particles. The temperature contours next to the wall shown in Fig. 4(d) are typical characteristics of expansion waves, which evidently propagate from the wall back into the flow region. These processes are labeled as EWwall in Fig. 4(b). The isobars and isopycnic contours (Figs. 4(c) and 4(b)) also indicate the presence of an expansion wave-like pattern propagating away from the wall, which...
FIG. 4. (a) Density contours in the gas flow domain generated by the propagating shock wave at various times. Distance normalized with $\psi_w$, time normalized with $\psi_w(m_w/\phi_0)^{1/2}$, and density normalized with $m_w/\psi_w^3$. (b) Density contours in the region of interest gas flow domain near reflecting wall generated by the propagating shock wave at various times. Distance normalized with $\psi_w$, time normalized with $\psi_w(m_w/\phi_0)^{1/2}$, and density normalized with $m_w/\psi_w^3$. (c) Pressure contours in the gas flow domain generated by the propagating shock wave at various times. Distance normalized with $\psi_w$, time normalized with $\psi_w(m_w/\phi_0)^{1/2}$ and pressure normalized by $\phi_0$. (d) Temperature contours in the gas flow domain generated by the propagating shock wave at various times. Distance normalized with $\psi_w$, time normalized with $\psi_w(m_w/\phi_0)^{1/2}$, and temperature normalized by $\phi_0/\kappa$. (e) Velocity contours in the gas flow domain generated by the propagating shock wave at various times. Distance normalized with $\psi_w$, time normalized with $\psi_w(m_w/\phi_0)^{1/2}$, and velocity normalized by $\sqrt{\phi_0}/m_w$. (f) Effect of piston stop location on stress distribution inside end wall. Case with piston stopped at 80 $\psi_w$ is identical to that stopped at 90 $\psi_w$. (g) Heat flux contours in the gas flow domain generated by the propagating shock wave at various times. Distance normalized with $\psi_w$, time normalized with $\psi_w(m_w/\phi_0)^{1/2}$ and heat flux normalized with $\phi_0/\psi_w^3 m_w^{1/2}$. (h) Pressure traces at various locations inside the flow field.
FIG. 4. (Continued).
subsequently interacts with the oppositely running expansion waves formed after the stop of the moving piston that is moving towards the end wall. The piston was stopped at about the $Y = 66\psi_w$ location and time $t = 15.5\tau_r$ to avoid an impact with the reflected shock. The data show that these expansion waves propagate towards the wall and interact face-on with the reflected shock, which they then penetrate. They subsequently reduce the flow density pressure and velocity in the region behind the reflected shock. These EW then interact with the weaker $EW_{wall}$ and their effects reach the wall at about $t = 21\tau_r$.

The arrival of the expansion waves associated with the arrest of the piston motion at the end wall takes place long after the arrival of the incident shock and it has no influence on the processes affecting directly the maximum gas pressure load and stress transmission into the wall. As will be discussed later, different piston stoppings at $80\psi_w$ or $90\psi_w$ have no impact on the generation and transmission of the initial stress wave and its magnitude within the solid phase of the end wall.
As the solid wall is impacted by the shock, its atoms are pushed in the downstream direction and therefore the wall deforms. Gas atoms, on the other hand, are pushed by the reflected shock in the upstream direction and move to a new bin location. Thus, no gas atoms are present at the first bin of the end wall after the shock reflection and therefore the gas density is zero there. Gas atoms at maximum density are located two bins upstream of the deflected end wall.

Figure 4(e) shows the velocity contours of the shocked gas particles ahead of the piston, which move with the same velocity as the piston. A large area of flow reversal is evident, extending up to a distance 110 \( \psi_w \) and clearly is caused by these expansion waves. At the wall, however, the mutual interaction between the impinging shock and the wall results in some additional phenomena. When the shock impacts the solid wall at \( Y = 115 \psi_w \), not only energy is exchanged but also the solid structure deforms, initially pushed and displaced in the downstream direction and subsequently in the opposite direction. This causes the gas flow to decelerate down to standstill and eventually change direction due to EW. Eventually the flow reversal region induced by the wall merges with that of the expansion waves caused by the piston stopping.

The transmitted stress inside the solid wall is shown in Fig. 4(f) for three cases of piston stops at locations \( Y = 66 \psi_w \), \( 80 \psi_w \), and \( 90 \psi_w \), respectively. The buildup of the stress as a function of time is identical in all three cases. The three traces start to deviate from each other after the maximum has been reached at about \( t = 21 \tau_r \). The two cases with the piston stop at \( Y = 60 \psi_w \) and \( Y = 88 \psi_w \) are identical in the range of time investigated here.

The energy associated with each atom is the sum of its kinetic energy and potential energy

\[
E_i = \sum_{j=1}^{N} \left( \frac{1}{2} U(r_{ij}) + \frac{1}{2} m_i (v_i)^2 \right),
\]

where \( m_i \) is the mass of atom \( i \), \( v_i \) denotes the (macroscopic) flow velocity on position of particle, \( r_{ij} \) is the velocity vector of atom \( i \), and \( U(r_{ij}) \) the pair-wise interaction between atoms \( i \) and \( j \) when separated by a distance \( r_{ij} \). Following Ref. 30, we can obtain for the heat flux

\[
q = \frac{1}{V} \left[ \sum_{i=1}^{N} r_i E_i + \frac{1}{2} \sum_{i=1}^{N} \sum_{j \neq i}^{N} r_{ij} (F_{ij} \cdot v_i) \right],
\]

where \( r_{ij} = r_i - r_j \) and \( F_{ij} \) is the force exerted on atom \( i \) by atom \( j \). The first term within the square brackets is related to convection and the second to conduction. However, solid particles with embedded atom interaction will have also embedding energy that needs to be added when calculating the heat flux in the solid structure.

The data in Figure 4(g) show that the distribution of the heat flux is mostly affected by the behavior of the gas molecular velocity. Considerable similarities are evident between the heat flux and the velocity contours in Figure 4(e) The heat flux reverses direction at \( t = 20 \tau_r \), and so does the velocity. The results also show that the heat flux increases across the propagating shock front. The heat flux reaches a maximum value that is about 25\% higher than that of the shocked gas behind the incoming shock during the process of shock wave reflection at the solid wall. This jump in heat flux is due to the conversion of kinetic energy into heat during the reflection as well as to heat conduction that takes place at the wall. The heat flux decreases at different times after the shock reflection takes place and then changes sign as the flow changes direction.

As mentioned earlier, the shock thickness is about 10 \( \psi_w \) and the pressure rise across it takes place within time \( t = 2.5 \tau_r \). Figure 4(h) shows pressure signals against time obtained at specific locations within the flow domain; the end wall is located at 114.36 \( \psi_w \). The pressure rise \( \Delta p/\Delta t \) appears to be 0.6/2.5 = 0.24 \( \psi_w \). The pressure rise of the reflected shock is considerably higher than that of the incident wave and in the region next to the wall is negative. This behavior can be attributed to the energy exchange between the flow and the wall. Further insight can be provided by considering the corresponding macro-scale relation (energy equation) in unsteady flows \( \frac{\Delta p}{\Delta t} = \rho \frac{D h_0}{D t} - \rho q \) where \( h_0 \) is the total enthalpy and \( q \) is the heat rate added to the system (negative in the present case). The term \( \rho q \) is activated during the reflection (being zero before) and therefore it contributes to the increase of \( \Delta p/\Delta t \). After the reflection is over the term \( \rho \frac{D h_0}{D t} \) becomes negative and overcomes the
The normal stress at the gas-solid interface is shown in Fig. 5. Continuity of normal stress is maintained during the shock impact on the solid structure in both gas and solid phases. When the shock impacts the solid wall, normal stress in both solid and gas increases to a maximum after the shock reflection takes place and decreases with the arrival of the expansion waves which cause a relaxation of the pressure load on the interfacial slab.

A. Energy exchange

In the MD model, the energy in the system is contributed by gas molecules through their potential and kinetic energy; wall molecules through their potential, kinetic, and embedded energy; piston molecules through potential energy and kinetic energy; holding wall molecules through potential energy and kinetic energy; ghost molecules through potential energy, kinetic energy and embedded energy. The total energy of the contributing systems remains constant but the amount of energy in each component of the shock model varies differently. In the following discussion, we focus is on the change in the energy of the gas and the solid wall molecules rather than the absolute value of energy.

Changes in energy can be found by evaluating each energy component at each time step and finding the difference in their magnitudes during and after the shock impact and reflection. However, the total change in energy can be also found by calculating the work done by the solid particles during their displacement. The magnitude of the change in energy by either method is the same. Figure 6 shows the energy change on the solid wall associated with the shock impact and the motion of the transmitted wave. Due to the energy exchange between gas particles and solid particles, there is a rise in the energy in the solid structure which results in an increase in stress and strain in it. The structure tends to revert to its unstrained state as the shock reflection takes place and the shock travels upstream. Figure 6 shows the energy gained by the solid particles of the end wall at four different initial gas density values. In addition to our standard case study (2708 gas particles), three other cases were simulated, involving either 2420, 2304, or 2132 gas atoms, with the same channel dimensions and the same acceleration time in all cases. Piston atoms were then allowed to move and stopped at the same time (i.e., location) in all three cases.

The results show that the shock impact will cause an increase in stress and strain of the solid structure and consequently the energy transmitted to the solid particles will increase. Moreover, shocks with higher speed will cause earlier impact. Hence, the increase in initial gas density will result in earlier and greater rise in the instantaneous energy gained by the solid particles.
B. Effect of the piston velocity

Additional tests were carried out in which the piston was moved at three different velocities, but stopped at the same location in all three cases. The simulations are continued to the same final time in all three cases. The time-dependent energy transmitted to the solid wall particles is shown in Figure 7 for the different piston velocities. It is apparent that the shock impact will result in an increase in energy gained by the solid particles which is proportional to the piston speed. The results also show an increase in piston velocity will result in an earlier and steeper rise in the energy gained by the solid particles.

IV. CASE 1: FREE-STANDING POROUS STRUCTURE

The porous structure was constructed by generating a block of solid particles and removing some of them to form circular poles. All dimensions of the gas channel remained the same and the removed particles were compensated by the ghost particles in a way that the total number of particles of the structure remained the same regardless of the number and size of the poles of the porous structure. In the structure shown in Figure 3(a) there are three rows of poles with three poles in each row for a total of nine poles. The first and third rows are in line with each other and the second is offset by half the distance between any two rows. All the poles have the same diameter and depth, set to $Y = 9.66 \psi_w$. The porosity is controlled by varying the poles' diameter and estimated as the number of atoms in the volume occupied by the poles only divided by the number of solid particles.
FIG. 8. (a) Pressure contours in the gas flow domain with free-standing porous structure with 96% porosity. Scaling as in fig. 4(b). (b) Pressure contours in the gas flow domain with free-standing porous structure with 80% porosity. Scaling as in fig. 4(b). (c) Pressure contours in the gas flow domain with free-standing porous structure with 66% porosity. Scaling as in fig. 4(b).

and ghost particles in that volume, \( \eta = \frac{N_{\text{solid}}}{N_{\text{solid}} + N_{\text{ghost}}} \). Although the poles were formed by selecting a desired value of the pole diameter, the porosity could not be calculated from this diameter because the position vector had discrete lattice values and there is a deviation between the desired diameter value and actual size of the generated poles.

Figures 8(a)–8(c) show the pressure contours in the flow domain at various times for three cases of porosity, \( \eta = 0.96, 0.80, \) and 0.65, respectively. The position and extent of the porous zone has been designated in these figures together with the end wall location. Part of the shock impacts the pole face and then is reflected back towards the piston: this is the primary shock wave reflection (PSWR), while the other part, the transmitted shock wave (TSW), propagates through the poles and eventually exits the porous structure. The exit sets up a set of expansion waves (EW) propagating in the opposite direction while the flow behind expands substantially. This flow has high kinetic energy and significantly lower pressure. Finally, the weaker than the original shock wave TSW will impact the holding wall and be reflected back into the gas channel. This reflection is designated as secondary shock wave reflection (SSWR). In each of these cases the maximum pressure associated with the PSWR occurs inside the porous structure.

As shown in these figures, the primary reflection is stronger with decreased porosity while the secondary reflection is weaker. For instance, in the case of \( \eta = 0.65 \), a pressure level behind the
primary reflected shock close to 1.9 is evident while a level close to 0.8 is observed in the high porosity case with $\eta = 0.96$. It should be noted that the pressure behind the primary or secondary reflection in the three cases of porosity investigated here is always lower than the value of 2.8 observed in the results of Figure 4(b). It should be noted that the secondary reflection resulted in a higher temperature rise than that of the primary reflection.

It is also interesting to observe the path of the EW generated by the arrest of the piston motion. They enter the porous zone at about $t = 20\tau_r$ and immediately interact with the EW associated with the TSW leaving the porous structure and entering a lower acoustic impedance region behind it. It appears that by the time the computations are terminated these EW had not exited the porous zone in all cases investigated here. Thus, in this case these EW never affected the end wall stress transmission and propagation. At the same time the SSWR reaches the back end of the porous zone at about $t = 20\tau_r$ in the case of $\eta = 0.96$ where is stronger while in the case of $\eta = 0.66$, when it is weaker, it is more than $8\psi_w$ behind the rear end of the porous zone.

The gas pressure distribution along the porous section between the solid particles poles is of interest. Since the shock wave is partially reflected at the poles’ frontal area and partially propagates inside the pores in the area between the poles, interactions between the flow fields behind the waves take place. Stagnating pressure in front of the poles leaks into the lower pressure region behind the propagating shock inside the pores. As a result of these interactions the maximum pressure always occurs in a region inside the porous zone. The flow of gas particles inside the pores is always accompanied by a pressure drop of the flow due to friction and heat dissipation. Substantially higher pressure drop occurs when the flow exits the pore region and expands into a larger volume between the porous structure and the holding end wall.

Figure 9 shows the variation of the gas pressure during shock impact at two locations inside the gas channel: the front section, across the slab adjacent to the porous structure, closer to the piston and the back section, on the slab adjacent to the porous structure, closer to the holding wall. Before the shock impacts the structure, the gas is at equilibrium. As the shock wave propagates inside the gas channel, it reaches the frontal area before the back area and consequently, the pressure rises due to shock impact/reflection at the frontal area. As time elapses, the flow exits the porous structure and the pressure rises at the back sections due to the reflection process that takes place at the holding wall. The pressure rise in both sections is highly dependent on porosity and its parameters: size, shape, placement, number, and length of the poles. The maximum pressure rise is inversely proportional to porosity. As porosity increases less frontal area is available and the primary reflection strength is smaller. At $\eta = 0.65$, the primary reflection is dominant and the pressure rise at the front area is much greater than that at the back area. The pressure difference across the porous structure appears to be inversely proportional to porosity. It is obvious that the pressure at the frontal area is much higher than that at the rear and hence the difference in pressure along the porous section will have

![Diagram showing gas pressure variation during shock impact](image-url)
FIG. 10. Pole orientation effect on the gas pressure during shock impact at front and back sections.

the same trend as that of pressure at the front section. The gas pressure is reduced when the EW associated with the piston’s motion arrest reach the front of the porous zone at about \( t = 20\tau_r \). As evident from the pressure data at the rear end of the porous structure, these waves never fully penetrated and exited the porous zone.

The effects of pole orientation on the gas pressure were investigated next with the porous structure turned 90° so that the poles are perpendicular to the flow direction as shown in Figure 3(b). A typical shock tube model that contains a free standing orthogonal straight pole arrangement with \( \eta = 0.80 \) was formed. The values of the gas pressure in the front and back areas of the porous section are compared to those in the case of parallel poles with \( \eta = 0.80 \).

According to Fig. 10, the gas pressure rise at the front area is higher in the orthogonal porosity case than that in the parallel porosity, whereas the gas pressure rise at the back area is less in the orthogonal porosity case. The flow in the orthogonal case faces a greater blockage area than that in the parallel and the primary reflection will be stronger. Moreover, the spacing between poles is smaller and therefore less particles flow through the porous section. As a result the pressure difference along the pores is greater in the case of orthogonal orientation of the porous material.

V. CASE 2: POROUS STRUCTURE ATTACHED TO A WALL

This porous structure was designed the same way the free-standing porous structure was generated. Some of the solid particles were removed to form circular poles that were attached to full layers of particles. The dimensions of the gas channel remained the same but only the solid wall structure (target) is changed. The poles are now attached to a solid wall (target) that has an axial length of 16.1 \( \psi_w \).

Figures 11(a)–11(d) show the pressure distribution along the gas channel at various times for four different porosities \( \eta = 0.96, 0.8, 0.65, \) and 0.52 respectively. A shock wave was formed and developed as discussed earlier and propagated in the gas channel till it reached the porous wall. Part of the shock impacts the pole face and then reflected back towards the piston: as in the previous case this is the primary reflection (PSWR), while the other part of the shock keeps propagating in the space between the poles, impacting the base of the wall and then is reflected backwards in the opposite direction a process designated as secondary reflection (SSWR). The data in these figures show that the secondary reflection results in higher pressure rise than the primary one at \( t = 0.20 \) with the exception of the case with \( \eta = 0.52 \). However, if a comparison to the data in Figure 4(b) (reference Case 0) is made one can conclude that in the case of porous wall, the pressure behind the reflected shock is always less than that occurring after a direct reflection over a solid wall. As porosity increases primary reflection strength weakens and secondary reflection becomes stronger. The outcome of this split reflection depends on the frontal reflecting area ratio. For the same depth
FIG. 11. (a) Pressure profiles in the gas channel with shock impacting a porous material structure with poles attached to end wall with 96% porosity. Scaling as in Fig. 4(b). (b) Pressure profiles in the gas channel with shock impacting a porous material structure with poles attached to end wall with 80% porosity. Scaling as in fig. 4(b). (c) Pressure profiles in the gas channel with shock impacting a porous material structure with poles attached to end wall with 66% porosity. Scaling as in fig. 4(b). (d) Pressure profiles in the gas channel with shock impacting a porous material structure with poles attached to end wall with 52% porosity. Scaling as in fig. 4(b).
FIG. 12. Variation of the change in energy of solid wall particles during shock impact on porous structures of different values of porosity.

of each test case lower porosity is equivalent to higher frontal area associated with the primary reflection. On the other hand higher porosity results in higher reflecting area in the back wall.

Of interest is a comparison of these data to the reference Case 0 data that were obtained in the case of a shock impacting a pure solid wall only, without any porous front structure. This case reference Case 0 is simply designated as a case with \( \eta = 1.00 \) porosity. The change in energy of the solid structure associated with the transmitted stress is computed by calculating the work done by the strained structure and plotted in Figure 12 for various values of porosity. The results show that less energy is transmitted to the target wall when a porous structure is attached at the front. This reduction in transmitted energy depends on porosity and is higher in structures with lower porosity. In fact in the case of a porous wall with \( \eta = 0.65 \) it is by 35% lower than that with \( \eta = 1.00 \). This clearly demonstrates the advantage of porous structures in attenuating the energy of the impact. There is also a time delay due to the presence of poles on the onset of energy transmission. Energy starts to build up earlier when the porosity is lower. In addition, the higher the porosity, the higher and steeper the transmitted energy during shock impact.

VI. CASE 3: POROUS STRUCTURE WITH GRADED POROSITY

Three different pole geometries have been considered in this case. In the first, Case 3.1, the porosity along the length of the poles changes gradually. Straight poles that were attached to the solid wall in Sec. V were replaced by poles of varying cross section. These poles are attached to 20 layers of solid particles that occupy an axial length of 16.11 \( \psi_w \). The removed particles are compensated by the ghost particles and the total number of particles of the structure remained the same regardless of the number and size of the poles. Referring to Fig. 3(d), there are three rows of poles with three poles in each row; this sums up to nine poles. The first and third rows are in line with each other and the second is offset by half the distance between any two rows. All the poles have the same shape and depth. The pole cross-sectional radius increases linearly from 0.2 at the tip to 4.0 at the pole’s base and the porosity is linearly decreasing from 99.23% to 48%. The average porosity is calculated by dividing the number of the solid particles forming the poles by number of the ghost and the solid particles contained in the porous section. The resulting average porosity is 80%. In the second Case 3.2 a mixed geometry was setup in which several of the conical poles were replaced by straight poles so that the average porosity was kept at 80%. In the last Case 3.3, inverse conical poles were used with increased porosity along (Figure 3(f)).

Figures 13(a)–13(c) show the pressure distributions at different times for the Cases 3.1, 3.2, and 3.3, respectively. Two distinct high pressure regions can be identified in Fig. 13(a), which are associated with the PSWR and SSWR. When some of the conical poles are replaced by straight poles the maximum pressure is mostly associated with the PSWR and it is formed inside the porous
zone (Fig. 13(b)). In this case the cross sectional area of the solid phase increases along the porous layer. The data of Case 3.3 shown in Fig. 13(c) indicate that the SSWR is responsible for the high pressure region formed close to the end wall. The effective cross section in this case remains about the same inside the porous layer.

Each of these pressure distributions should be directly compared to the pressure distribution over a solid wall in the absence of any porous structure shown in Figure 4(b). Such a comparison demonstrates that the maximum pressure in any of the three cases with a porous structure is smaller than the maximum pressure over a solid wall. The obvious question now is which geometry and arrangement provides the least maximum load and transmits the minimum energy to the end wall. A closer inspection of the numerical values indicated that Case 3.1 showed the largest stress among the three cases case with graded porosity while Case 3.3 and 2.0 showed the smallest stress.

The change in energy of the solid structure is computed in the way described earlier. Fig. 14 shows that the pure solid wall Case 0 has the highest change in energy deposited in the target structure. The graded pole Case 3.1 has the highest change energy of all porous cases followed by the mixed geometry with straight poles Case 3.2, while the last two cases-mix graded (increasing and decreasing thickness) and straight pole case – i.e., Case 3.3 and Case 2 have the lowest change in energy.
VII. CONCLUSIONS

In the present work molecular dynamics was implemented to investigate the interaction of shock waves with nano-structured materials. These materials have the potential to dissipate drastically fast traveling shock or blast waves at nano-scales because their surface-to-volume ratio is substantially higher than in the case of macro-scale materials.

The simulated system was a nano-scale model of a laboratory shock tube. The end wall represents a solid wall target covered with a nano-structured porous material which provides the required protection. A moving piston in a stagnant gas used to generate a shock wave traveling upstream through the gas molecules towards the solid wall target. The gas and porous solid were modeled by Lennard-Jones-like and effective atom potentials, respectively. The heat flux vector was evaluated using relations which do not assume or invoke any constitutive law between heat flux and temperature gradients. This platform based on MD calculations allows for spatially-resolved information of the flow within the moving shock during its interaction with the nano-scale material, a capability which is not present in computations using the classical Navier-Stokes equations. In the present nano-shock tube setup, the shock has a finite thickness and the process of shock reflection over the end wall is fully resolved in time and space. The present computations revealed that this reflection is gradual and therefore the reflected shock interacts with the yet-to-be-reflected part of the incoming shock wave. As a result of this interaction of the reflected shock with itself, the values of pressure and density in the near wall zone are considerably higher than the values obtained further away. This is the most striking difference between the present case, where the shock itself is resolved, and the classical macro-scale instantaneous shock reflection over a wall. Secondary differences include the energy exchange between the heat conducting end wall and the shock or flow field which usually is not present in the macro-scale computations.

Several cases of a free standing porous structure, a porous structure attached to a wall and porous structures with graded porosity were investigated. The effects of pore shape and orientation have been also considered. In order to provide a reference for comparison, the case of the shock impacting the target wall directly in the absence of a protective material was extensively investigated and documented first. The porous structure was generated by considering a block of solid particles and removing some of them to form circular poles.

In all cases, we focused on the change in the energy of the gas and the solid wall molecules before, during and after the interaction of the shock wave with the material structure. During the interaction, part of the shock impacts the pole face and then is reflected back towards the piston (PSWR) while the remaining part of the shock keeps propagating in the space between the poles, impacting the base of the wall and then is reflected backwards in the opposite direction (SSWR). The strength of each of these two reflections depends mostly on the porosity of the material. In low porosity cases the PSWR is stronger while in high porosity cases SSWR is stronger.
The results of this work indicate that the presence of nano-porous material layers in front of the target wall provides beneficial effects on its survivability. The deposited energy in the target wall is decreased when compared to the non-protected target case which is equivalent to a fully porous material with 100 percent porosity. The loading rate of the target wall also decreases which further protects the integrity of the structure. Porosity, shape and orientation of the pore structures affect the interaction and the amount of deposited energy on the structure. A decrease in porosity by 35% results in a reduction in the deposited energy level by an equal percentage. Porous materials with straight poles or graded porosity with increasing/decreasing thickness of conical poles possess the greatest promise in reducing the deposited energy.

ACKNOWLEDGMENTS

The financial support provided by NSF under Grant CCI-0800307 is greatly appreciated.


