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Fast-condensing nanofoams: Suppressing localization of intense stress waves

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ABSTRACT

We investigated the propagation of intense stress waves across silica nanofoams, with the pore size ranging from ~50 nm to ~1 μm and the porosity of ~60%. The experimental results showed that if the pore size was relatively large, the stress wave remained localized and its energy was dissipated in narrow bands; if the pore size was below ~200 nm, however, the stress wave was homogenized in a broad area and consequently, bulk distributed energy absorption was promoted and the maximum transmitted-wave pressure was significantly reduced. We attribute this phenomenon to the fast condensation of the smallest pores at the wave front. The ability of nanofoams to promote widespread energy absorption may enable efficient stress-wave mitigation techniques. The classic Grady model was modified to take account for the nanopore size effect.

1. Introduction

Associated with intense dynamic shear loading, a stress wave can be localized [1,2]; that is, the wave front may become non-uniform in transverse directions. An intense stress wave is often nonlinear; i.e., nonlinear material behaviors, e.g. internal damaging, dominate the wave propagation and dissipation. Under this condition, many concepts of linear wave theory, such as acoustic impedance and wave energy conservation, may break down. For instance, as a nonlinear stress wave advances into a solid material, it can cause plastic yielding, micro-cracking, and/or local phase transformation [3–7]; in a foam material, it may trigger cell buckling and ligament rupture [8,9]; in a granular material, it can activate rearrangement of close-packed components [10,11]. The nonlinearity is often coupled with the stress wave localization [12–14]; i.e., an initially uniform wave front may become localized and the wave energy is dissipated in a number of narrow zones, e.g. shear bands [3,10,15,16]. The instability of stress wave can be caused by either material instability or geometrical instability [1]. Over the years, the stability of stress waves was extensively investigated [1,10,11,17–21]. Shear-band nucleation, propagation, and morphology change were related to materials properties and loading modes. However, there still lack efficient methods to "disperse" intense stress waves and to promote widespread energy absorption.

For each material and loading condition, when an intense stress wave is localized, the shear deformation zone (SDZ) has a characteristic width, w, ranging from a few nm in metallic glass [22] to hundreds of μm in foam materials [8] or granular materials [23,24]. For brittle solids, based on the equilibrium condition of kinetic energy and strain energy, Grady [25,26] developed a model to predict the fragment length:

$$L = \left(\frac{\sqrt{24} K_c}{\rho C \dot{\varepsilon}} \right)^{2/3} \quad (1)$$

where K_c is the fracture toughness, ρ is the mass density, C is the speed of sound, and $\dot{\varepsilon}$ is the strain rate. This framework can be applied to analyze both the spacing and the size of SDZ. It captures the effects of strain rate and resistance to shear [27,28]. The Grady model has successfully explained many experimental observations of solid and porous materials [27,29–31]. It suggests that the SDZ size (w) is independent of the characteristic length of the material, e.g. the pore size (d).

Foams are solid materials containing empty cells or pores [32]. A few examples of foams include bones [33,34], woods [34,35], carbon nanotube bundles [36], and porous polymers/metals/ceramics [37–39]. In general, foams are lightweight. They are widely applied for thermal insulation, acoustic damping, and impact and vibration protection [32,40]. In a foam material, if a stress wave becomes localized, catastrophic failure would take place in narrow shear bands, with the majority of the protection capacity being "wasted". In a regular foam material where the pore size is

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Nomenclature

A	cross-sectional area used in the calculation of acoustic impedance
A_b	cross-sectional area of the Hopkinson bars
C	speed of sound used in the Grady model
C_b	speed of sound of the Hopkinson bars
d	pore size
D	diameter of the loading rod
D_r	inner diameter of the support ring
E_b	Young's modulus of the Hopkinson bars
F	peak force
K_c	fracture toughness
L	fragment length
m	sample mass
p	porosity
p_2	nominal two-dimensional porosity of a nanofoam sample
p_2^*	nominal two-dimensional porosity of a pristine nanofoam sample
P_{Hg}	infiltration pressure of mercury
P_{Pi}	Average maximum incident-wave pressure
P_{t0}	equivalent maximum normal stress
P_{tc}	maximum transmitted-wave pressure in dynamic compression
P_{ts}	maximum transmitted-wave pressure in dynamic shearing
P_w	stress-wave pressure
r	radius of the loading rod
S_0	quasi-static shear strength
t	sample thickness
T	temperature
T_P	pulse duration
U	energy associated with stress wave
U_i	energy associated with incident stress wave
U_k	kinetic energy associated with local particle velocity
U_r	energy associated with reflected stress wave
U_s	strain energy associated with local deformation
U_t	energy associated with transmitted stress wave
v	impact velocity of the striker
V	volume of the material that undergoes permanent structural changes
w	shear-deformation-zone size
z	acoustic impedance of nanofoam sample
β	energy dissipation factor
ε	strain
$\dot{\varepsilon}$	strain rate
ρ	mass density (mass divided by sample volume)
ρ_b	mass density of the Hopkinson bars
ρ_s	mass density of solid amorphous silica
ς	pressure reduction factor

relatively large, e.g. comparable with or larger than the typical SDZ size, the cell buckling at the stress wave front may be viewed as a process that reduces the shear resistance; thus, wave energy dissipation tends to be limited within a number of narrow bands. In the current study, we investigate nanofoams in which the pores are nano-sized, much smaller than the typical SDZ size. In such a material, cell buckling may be viewed as a fast condensation mechanism, which increases the effective local shear resistance. As the shear banding is suppressed, bulk-distributed energy absorption may be promoted.

2. Methodology

2.1. Materials and specimens

In the current investigation, we processed a set of monolithic silica foam samples. The pore formation was achieved by sol-gel methods [39,41,42], and the porous structure was precisely controlled by a subcritical calcination (SCC) process [43]. The details of the sample preparation have been documented in Appendix A.

The pore formation agents were polyethylene glycol (PEG) for large pores, or potassium silicate for small nanopores. After phase separation, they were eliminated through acid washing. Then, the samples were dried at 80 °C for 3 days in a VWR 1330GM oven, and subcritically calcinated at temperatures slightly higher than the glass transition point of amorphous silica glass, 1200 °C, for 1 h in a MTI GSL-1700X horizontal tube furnace. The ramp rate was initially set as 3 °C/min; and when the temperature was 100 °C away from the target temperature, the ramp rate was reduced to 1 °C/min. After the SCC procedure, cooling was conducted at a rate of 3 °C/min to minimize the residual stress.

The processing conditions and the key material parameters of the silica nanofoams are shown in Table 1. The testing samples were disk-shaped, with the diameter of ~23 mm and the thickness of 4.50 mm. Fig. 1a shows the X-ray diffraction (XRD) analysis results. Fig. 1(b–d) show the morphology of silica nanofoams.

2.2. Mechanical testing

2.2.1. Shear-promotion-support-ring system

The shear-promotion-support-ring (SPSR) system, as shown in Fig. 2a, included a front part and a rear part made of 17–4 PH stainless steel. As depicted in Fig. 2b, a silica nanofoam disk was mounted between the front part and the rear part, with an thin layer of petrolatum applied on each interface to reduce potential friction and to smoothen stress wave transmission. A loading rod with the outer diameter of 12.7 mm was compressed against the surface of the sample. At the back of the silica disk, the support ring and the steel plate on the rear part were used to support the sample. The inner diameter of the support ring was 13.1 mm, slightly larger than the outer diameter of the loading rod; the

Table 1
Processing conditions and properties of silica nanofoams.

Component mass ratio	TMOS to PEG	Colloidal silica to potassium silicate							
	5.5:1.0	1.3:98.7	7.5:92.5	12.5:87.5	17.0:83.0	22.5:77.5	27.5:72.5	35:65	40:60
SCC temperature (°C)	1230	1260	1262	1260	1258	1254	1251	1239	1228
Pore size range	[780,1980]	[240,390]	[190,290]	[150,220]	[130,180]	[100,140]	[70,100]	[60,80]	[40,60]
Average pore size (nm)	1380 ± 600	315 ± 75	240 ± 50	185 ± 35	155 ± 25	120 ± 20	85 ± 15	70 ± 10	50 ± 10
Porosity (%)	59.6 ± 2.7	62.7 ± 0.9	61.6 ± 0.9	60.7 ± 1.2	59.5 ± 0.8	62.4 ± 1.4	59.1 ± 2.0	60.0 ± 1.5	60.0 ± 1.3