The properties of copper foams with negative Poisson's ratio via resonant ultrasound spectroscopy

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Dong Li,[*1] Liang Dong,[2] and Roderic S. Lakes[*3]

1 College of Sciences, Northeastern University, Shenyang 110819, PR China
2 Materials Science Program, University of Wisconsin, Madison, WI 53706-1687, USA
3 Department of Engineering Physics, University of Wisconsin, Madison, WI 53706-1687, USA
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* Corresponding authors: e-mail lakes@engr.wisc.edu, Phone: +00 608 265 8697, Fax: +00 608 263 7451; e-mail lidong125930@gmail.com

The Poisson's ratios of re-entrant Cu foams with different initial relative densities were studied by resonant ultrasound spectroscopy (RUS). Slight anisotropy in foam was detected by RUS and removed by a small unidirectional compression. The transformation into the re-entrant foam was accomplished by applying a sequence of permanent triaxial compression deformations. The Poisson's ratio first decreases and then increases with increasing compression strain. A minimum in Poisson's ratio of approximately -0.7 for all initial densities was achieved with an appropriate permanent compression strain, compared with -0.6 at similar density determined earlier via optical methods. Foams with higher values of initial density attained minima in Poisson's ratio at lower permanent volumetric compression. The shear modulus increased with increasing volumetric compression ratio, and showed a small hump near the point corresponding to Poisson's ratio minimum.

1 Introduction

Synthetic cellular solids are used in the form of structural honeycombs (two dimensional cellular solids) for lightweight sandwich panels in aircraft and other structures. Foams as three dimensional cellular solids are also used as core in sandwich panels and for packing, cushioning, energy absorption applications, structural purposes and thermal protection systems. Physical properties of cellular solids depend on the properties of the solid material that makes up the cell ribs, on the relative density, cell shape, cell size and on loading conditions, as presented by Gibson and Ashby [1]. The relative density is the dimensionless ratio of the bulk density of the foam material to the density of the solid from which it is made.

Isotropic foam structures with negative Poisson's ratios have been fabricated and characterized by one of the authors [2]. Control of the Poisson's ratio is done by changing the cell structure of the foam. Specifically the cell structure is changed from a convex polyhedral shape to a concave or "re-entrant" shape. The method used depends on the kind of foam. For polymer foams, the material is triaxially compressed, heated above the softening point, and cooled. For ductile metal foams, the material is compressed permanently in increments to attain a triaxial compression of appropriate magnitude. The transformation increases the relative density substantially. Negative Poisson's ratio gives rise to a predicted increase in some material properties such as flexural rigidity and plane strain fracture toughness [3]. Re-entrant transformation of copper foam resulted in an increase in observed indentation resistance, [4], consistent with theory [5]. Many other materials with a negative Poisson's ratio, also known as auxetic materials, have been reported; the role of Poisson's ratio including negative values has been reviewed [6][7][8]. Poisson's ratio effects in anisotropic materials including single crystals may be accompanied by cross coupling effects such as stretch-shear coupling, so appreciation of such effects tends to be less intuitive than in isotropic materials. The range for Poisson's ratio ν is $-1<\nu<0.5$ for *isotropic* materials based on stability conditions in the theory of elasticity. Common isotropic materials including most foams have Poisson's ratio in the range $0.25<\nu<0.35$. The range of Poisson's ratio approaching -1 in isotropic materials corresponds to unusual behavior. Therefore exploration of the lower limit attainable in foams is of interest.

The Young's and shear moduli and Poisson's ratio of all foam materials has a nonlinear dependence on strain because the cell ribs realign under deformation. For example, negative Poisson's ratio polymer foam exhibits a minimum in Poisson's ratio near zero strain [9]. Negative Poisson's ratio metal foams also exhibit a minimum in Poisson's ratio near zero strain [10]; this minimum is much sharper than the one for polymer foams. The optical method used to determine the Poisson's ratio in the metal foam required a specimen surface strain up to 10^{-4}. In all foams, the local strain may exceed the global strain, so the method may not reveal the detailed behavior in the vicinity of minimum Poisson's ratio, owing to material nonlinearity. In particular the true minimum in Poisson's ratio could depend on strain level, even at small strain, in metal foam.

In this study, the mechanical properties of both conventional and re-entrant copper foam materials are examined by resonant ultrasound spectroscopy (RUS) [11]. Maximum strain in RUS is very small, less than 10^{-6}. This is advantageous in studying highly nonlinear materials such as these.

2 Experimental methods

2.1 Specimen processing

Three copper foam cube specimens with sizes of 35 x 35 x 35mm, 31 x 31 x 31mm and 31 x 31 x 31mm and relative densities of 0.057, 0.039, 0.032, respectively, were cut from large blocks of commercial copper foam (Astro-Met, Cincinnati, OH) with a low speed diamond saw. The specimens were then sanded and polished to ensure a near perfect cube.

The foam as received is slightly anisotropic due to gravitational effects during manufacture. In order to achieve a microstructure that is isotropic or nearly so, the following method was applied. Elastic anisotropy of the specimen was determined by the splitting of resonant peaks in the RUS spectrum. To reduce the anisotropy, the specimen was compressed in one of the orthogonal directions. A subsequent RUS spectrum was obtained to determine the amount of peak splitting (5% - 10%), hence the anisotropy. If the permanent compression reduced the anisotropy, additional permanent compression was applied to obtain a nearly isotropic specimen for which peak splitting was negligible (less than 1%). If the permanent compression increased the anisotropy, then permanent compression was applied in a different direction and the procedure repeated to obtain an isotropic specimen. The specimen was then sanded and polished to ensure a near perfect cube.

The cube specimens were then transformed into re-entrant structure by applying with a vise a sequence of consecutive plastic compressional deformation (less than 2% strain for each iteration) from three orthogonal directions aligned with the cube surfaces. Measurements of elastic constants were conducted after each step of triaxial compression.

2.2 Microstructure

Reflection optical microscopy observations (with an Olympus SZH10 stereo-zoom microscope) were performed to evaluate the microstructures of re-entrant copper foams in three orthogonal directions. The as-received foam showed no obvious structural anisotropy (Fig. **1**).

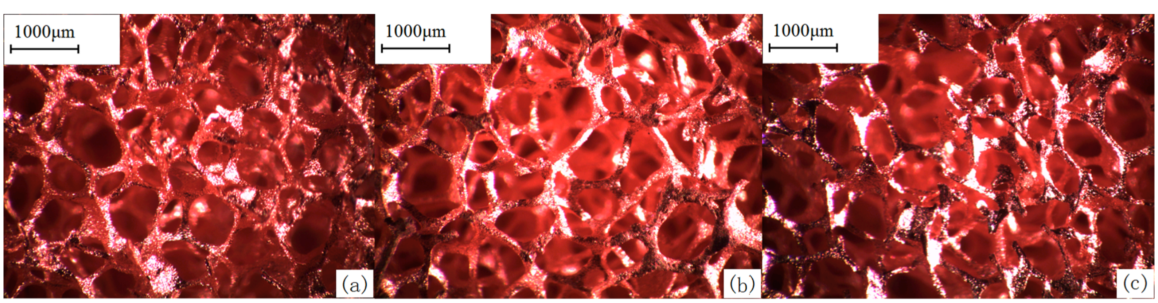

Fig. 1 The microstructures (optical, reflected light) of copper foam in three orthogonal directions. The scale bar is 1000 μm.

2.3 Resonant ultrasound spectroscopy (RUS)

The rationale for using this method is that it operates at small strain levels, less than 10^{-6}, well within the linear range of behavior. As described above, these foams exhibit nonlinearity in the dependence of

Young's and shear modulus and Poisson's ratio upon strain. Conventional mechanical testing methods may return results in the nonlinear range of behavior. Moreover, deformation of the entire volume of the specimen is sampled in RUS, not just the surface.

The mechanical properties of the foams were characterized using resonant ultrasound spectroscopy. RUS measurements were performed to obtain a complete spectrum, from which the shear modulus G and the Poisson's ratio ν were inferred. The transducers used were Panametrics V153 1.0/0.5 broadband shear transducers. These are polarized with center frequency 1 MHz. Shear transducers were used because they provide a stronger signal than compressional transducers for some modes, especially for the crucial fundamental torsional mode [12]. Moreover shear transducers enable the identification of modes by virtue of polarization sensitivity. A signal from a digitally synthesized function generator was input to the driver transducer. The receiver transducer output was amplified by a preamplifier. The amplifier's band-pass was 100 Hz-300 kHz and the gain was from 100 to 1000. The function generator (Stanford Research DS 345) has a quoted frequency resolution of 1 Hz, and an accuracy of 5 ppm. The signals were captured by a digital oscilloscope (Tektronix TDS 3012B). The experimental configuration is shown in Fig. 2. Computer methods were used to generate plots of mode structure for interpretation as described below, rather than to automatically reduce data. Contact force was minimized by adjusting the position of one transducer using a vertical stage adjusted with a fine micrometer drive (Newport type MVN50) in order to minimize shifts in resonant frequencies, hence errors in the moduli.

The torsion fundamental natural frequency is given for isotropic cubes [13] by the following:

$$f_0 = \frac{\sqrt{2}}{\pi L}\sqrt{\frac{G}{\rho}} \qquad (1)$$

in which f_0 is the frequency in Hz, L is the specimen length, G is the shear modulus, and ρ is the specimen density. There are higher torsion modes at integer multiples of the fundamental.

The shear modulus was determined by the identification of the lowest torsional mode and the use of Eq. (1). The Poisson's ratio was determined by aligning the observed mode structure with the Demarest plot. The Demarest plot of mode structure vs Poisson's ratio for an isotropic cube over the full range of Poisson's ratio has been numerically created recently by the authors [14]. This graphical approach is insensitive to imperfections, such as heterogeneity, in the specimen because the lowest few modes suffice to determine the isotropic elastic constants. This is in contrast to the numerical inversion method used for perfect single crystals; many modes are needed for convergence; the algorithm will not converge if the specimen is slightly heterogeneous or deviates somewhat from the assumed crystal symmetry.

As for heterogeneous solids such as foams, the resonance method has the further advantage that properties are inferred from deformation throughout the volume of material rather than from motion at points at the boundary. Surface measurements, because they are local in nature, are likely to be more influenced by material heterogeneity than measurements through the volume.

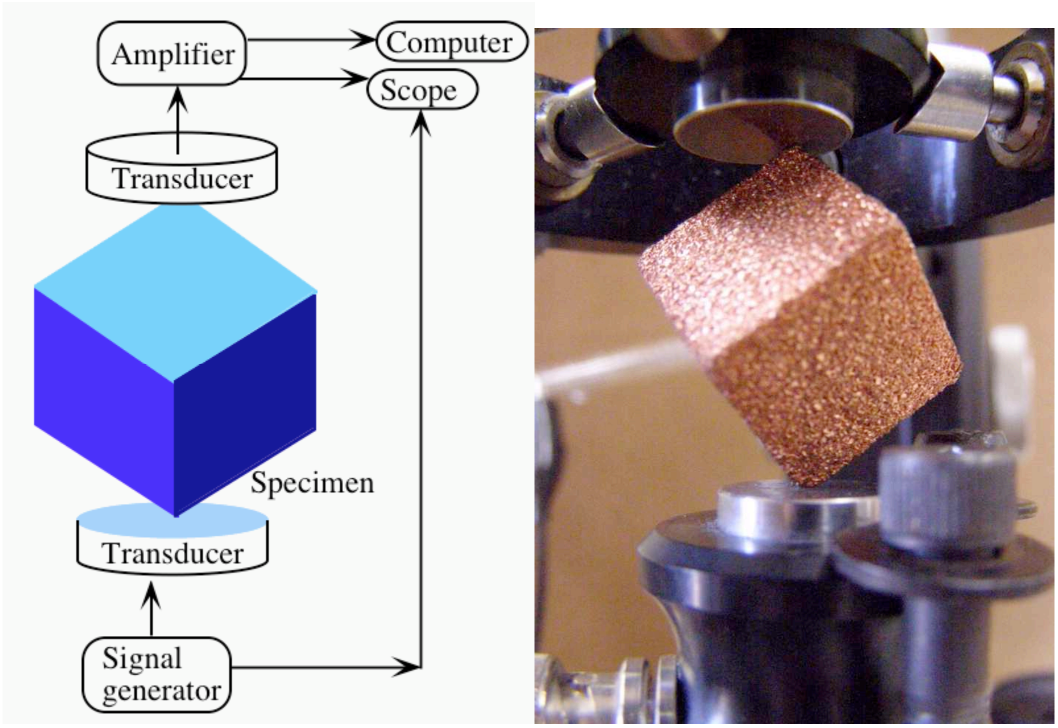

Fig. 2 Resonant ultrasound spectroscopy apparatus, left, diagram, right, photograph.

3 Results and discussion

Fig. 3 shows the relationship between the Poisson's ratio and the volumetric compression ratio for copper foams with various initial relative densities of 0.057, 0.039 and 0.032. The as-received foam has a Poisson's ratio in the range 0.2 to 0.3, which is reasonable. It can be seen from Fig. 3, that all the specimens exhibited a minimum in the curve of Poisson's ratio vs. volumetric compression ratio. A minimum Poisson's ratio as small as approximately -0.7 was achieved. The copper foam with a lower initial relative density requires a higher volumetric compression ratio to achieve the Poisson's ratio minimum.

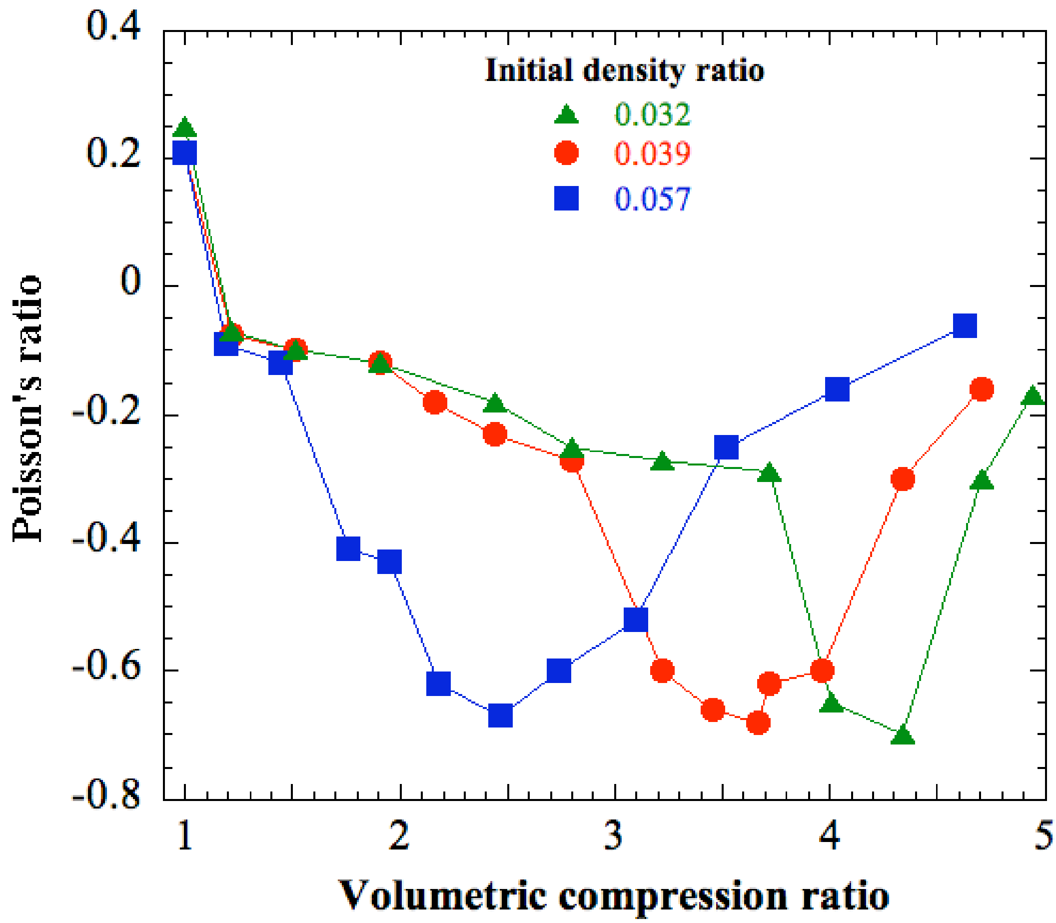

Fig. 3 Poisson's ratio vs. volumetric compression ratio for copper foams with initial relative densities of 0.057 (squares), 0.039 (circles), and 0.032 (triangles).

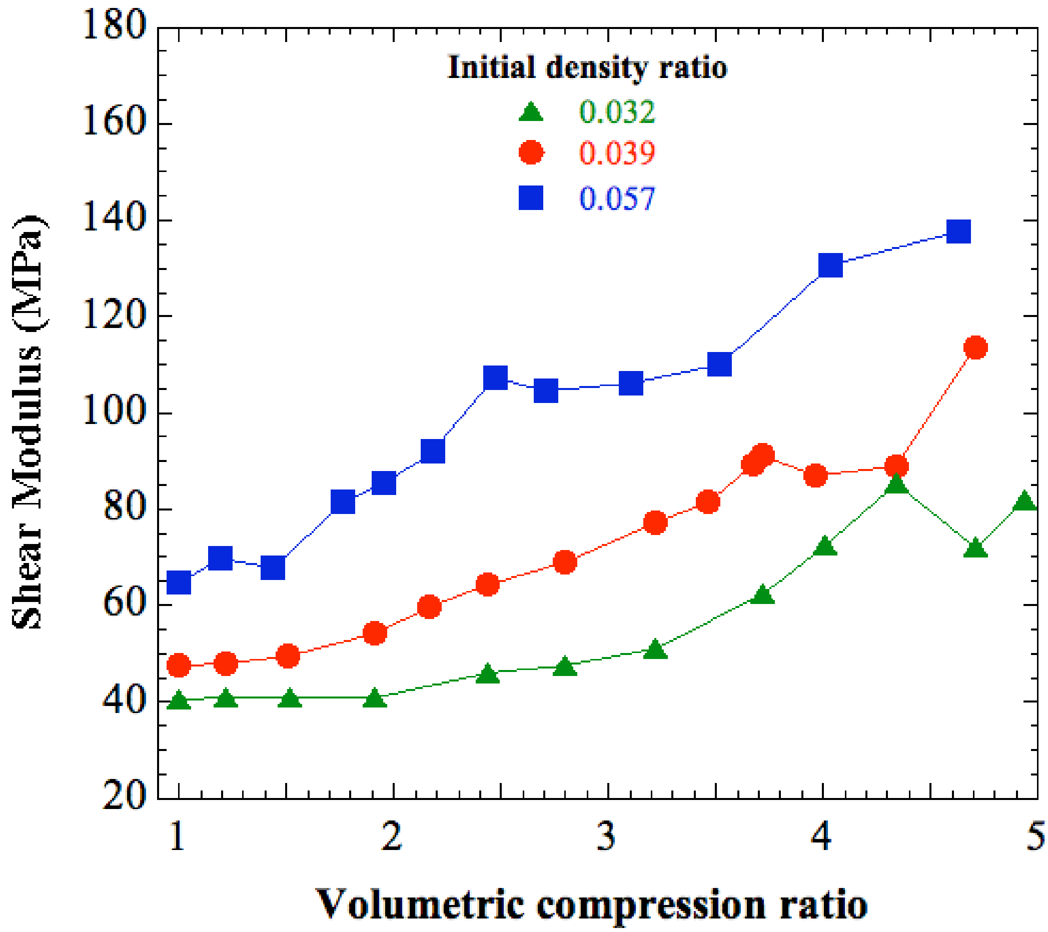

Fig. 4 Shear modulus vs. volumetric compression ratio for copper foams with different initial relative densities of 0.057 (squares), 0.039 (circles) and 0.032 (triangles).

Fig. 4 shows the shear modulus vs. volumetric compression ratio for copper foams with various initial relative densities of 0.057, 0.039 and 0.032. The shear modulus increases with increasing volumetric compression ratio, and shear modulus curve exhibited a small hump near the volumetric compression ratios which give rise to the Poisson's ratio minimum. Prior experiment with copper foams revealed Young's modulus not shear modulus, with fewer data points than the present results. The hump in the shear modulus is attributed to a favorable orientation of cell ribs near the optimal compression ratio. Shear modulus is overall higher in foams with higher relative density as expected. The observed increase in shear modulus with increasing volumetric compression ratio is associated with increasing foam density and also with a change in microstructure as the cells fold in following permanent compression.

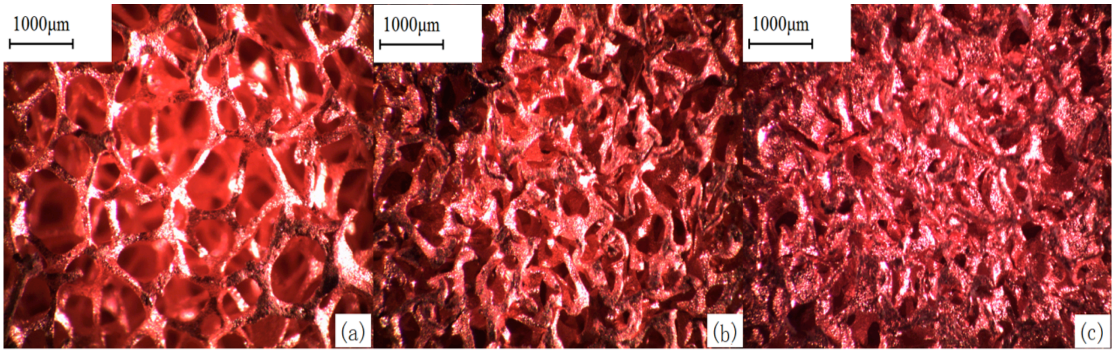

Fig. 5 The microstructures (optical, reflected light) of copper foam with volumetric compression ratio of (a) 1, (b) 4.34, and (c) 4.94, respectively. This copper foam has an initial relative density of 0.032. The scale bar is 1000 μm.

Fig. 5 shows the microstructure images of the copper foam with initial relative density of 0.032 at the volumetric compression ratios of (a) 1, (b) 4.34 and (c) 4.94, respectively. Fig. 5(a), (b) and (c) correspond to a Poisson's ratio of 0.25, -0.7, and -0.15, respectively. The conventional foam shows the open cells with a size of approximately 1 mm in diameter.

Permanent volumetric compression alters the angle of the cell ribs, consequently the Poisson's ratio. Sufficient compression results in an inward bulging re-entrant cell structure. Permanent compression beyond the optimal value may give rise to a less favorable geometry, even to contact between the ribs, causing an increase in Poisson's ratio.

Metal foams differ from polymer foams in that permanent deformation occurs at much smaller strain in the case of the metal. Ductile metal foam can therefore be processed to a re-entrant structure at ambient temperature. However, nonlinearity in material properties occurs at smaller strain in metal foam than in polymer foam.

The minimum Poisson's ratio observed at small strain via RUS in the present study is somewhat smaller (-0.7) compared with the minimum (-0.6) observed previously via optical methods for similar density but at higher strain. Foam of higher initial density was not available for the present study; a minimum Poisson's ratio of -0.7 was observed in higher density foam. One may consider whether lower Poisson's ratio is possible in isotropic materials. This is of interest because as the Poisson's ratio approaches -1, the material easily undergoes volume change when deformed, in contrast to the shape change governed by the shear modulus. Poisson's ratio tending to the isotropic lower limit -1 is in fact certainly possible. For example, hierarchical laminates with high contrast between phases can have Poisson's ratio approaching -1 as the contrast increases without bound [15]. In (two-dimensional) honeycomb with hexagonal cells, Poisson's ratio can be tuned to negative values including -1 by proper choice of cell dimensions and angles [16]; isotropic in-plane behavior is possible. Related two dimensional paradigms include rotating hexamers [17] and hinged squares and other polygons [18]. In chiral honeycomb [19] containing nodes that rotate, Poisson's ratio is -1, independent of strain and isotropic in-plane. Such honeycomb has been studied in the context of aircraft applications [20] [21]. In these cellular solids the in-plane bulk modulus is governed by rib bending, but for the proper geometry, shear requires rib extension. For slender ribs, the ratio of stiffness is so large that the bulk modulus is much smaller than the shear modulus, giving a Poisson's ratio that tends to -1 in some regular two dimensional structures. By contrast, in the foams, the structure has a random component. Alignment of the ribs in foam, which has less order than honeycomb, will have a distribution of angles, so the limit on Poisson's ratio is not attained.

4 Conclusions

1 A minimum in Poisson's ratio of approximately -0.7 was achieved in re-entrant copper foam with an appropriate compression strain. The minimum in Poisson's ratio is somewhat smaller than with prior results at similar density obtained by optical methods at higher strain.

2 The Poisson's ratio minimum shifted to the points corresponding to lower volumetric compression ratios with increasing initial relative density.

3 The shear modulus increased with increasing volumetric compression ratio, and showed a small hump near the point corresponding to Poisson's ratio minimum.

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