Chapter 5

The Effect of Strain Rate on the Yielding Mechanism of Amorphous Metal Foams

Abstract

Highly stochastic amorphous $Pd_{43}Ni_{10}Cu_{27}P_{20}$ foams were tested in quasi-static and dynamic loading. The strength/porosity relations show distinct slopes for the two loading conditions, suggesting a strain-rate-induced change in the foam yielding mechanism. The strength/porosity correlation of the dynamic test data along with microscopy assessments support that dynamic foam yielding is dominated by plasticity rather than elastic buckling, which was previously identified as the mechanism governing the quasi-static yielding of these foams. The strain-rate-induced shift in the foam yielding mechanism is attributed to the convergence of the characteristic time for dynamic loading and the timescale associated with sound wave propagation across intracellular membranes, thereby suppressing elastic buckling and promoting plastic yielding.

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Introduction

Recent progress in the processing of metallic glasses has led to the development of open-and closed-cell amorphous metal foams fabricated from various alloys via a variety of methods [42, 43, 56, 60, 61, 62]. Because of the unique mechanical properties of amorphous metals, such as high strength and elasticity, broadly varying toughness, and lack of ductility [12], amorphous metal foams have been shown to inherit a collection of mechanical properties from the parent material not previously seen in porous solids of any kind. Specifically, cellular structures consisting of struts thinner than the process zone size of the amorphous metal were found to be heavily deformable, as catastrophic failure due to global brittle fracture is effectively avoided [30, 34]. On the other hand, highly stochastic cellular structures consisting of struts with broadly varying thicknesses and aspect ratios were found to yield by percolation of elastic buckling instabilities, a consequence of the high elastic limit of the amorphous metal [35]. The elastic yielding behavior of such highly stochastic foams gives rise to a steep strength/porosity relation, resulting in very high strengths and significantly more plasticity than monolithic (pore-free) materials at high relative densities [29], however as the limit of cooperative buckling is approached at low relative densities, the attainable foam strengths are substantially lower. By matching the structural scales controlling brittle fracture and buckling percolation, that is, by attaining cellular structures consisting of thin struts with uniform slenderness ratios, the foams can yield plastically at rather low relative densities (<10%) [36]. Consequently, such foams are able to inherit the high plastic yield strength of the amorphous metal at very high porosities, and thereby emerge among the strongest foams of any kind.

The mechanical behavior of monolithic amorphous metals is known to be insensitive to strain rate [13, 63], but the strain-rate sensitivity of these porous solids has not yet been investigated. In this chapter, it is shown that unlike the parent solid, the yielding mechanism of a stochastic amorphous-metal cellular structure is sensitive to the rate of the applied strain, and consequently the slope of the overall strength/porosity relation for the foam material shifts with a drastic increase in the strain rate.

Methods

Amorphous $Pd_{43}Ni_{10}Cu_{27}P_{20}$ foam specimens with highly stochastic closed-cell porosity were utilized in this work. The foams were produced by thermoplastically expanding entrained bubbles in the supercooled liquid region, as described in Ref. [39]. The statistical distribution of pore sizes in such foams is analyzed in Ref. [57]. Dynamic and quasi-static compression tests were carried out on plane-parallel cylindrical specimens with relative densities ranging from 13% to 65%. For the dynamic tests, specimens with heights of about 6 mm were used. A representative dynamic-test specimen is shown in figure 5.1(a). For the quasi-static tests, specimens with aspect ratios around 1.0 were used. Porosities of all samples were measured using the Archimedes method.

For the quasi-static tests, a screw-driven Instron universal testing machine with a load capacity of 50 kN was used. Displacements were measured using a linear variable differential transformer. Strain rates for the quasi-static tests ranged between 10^{-3} and 10^{-4} s^{-1}. The dynamic compression experiments were carried out on a 19.05 mm diameter split Hopkinson (Kolsky) pressure bar made of C300 Maraging steel at strain rates between 3000 and 3500 s^{-1}.

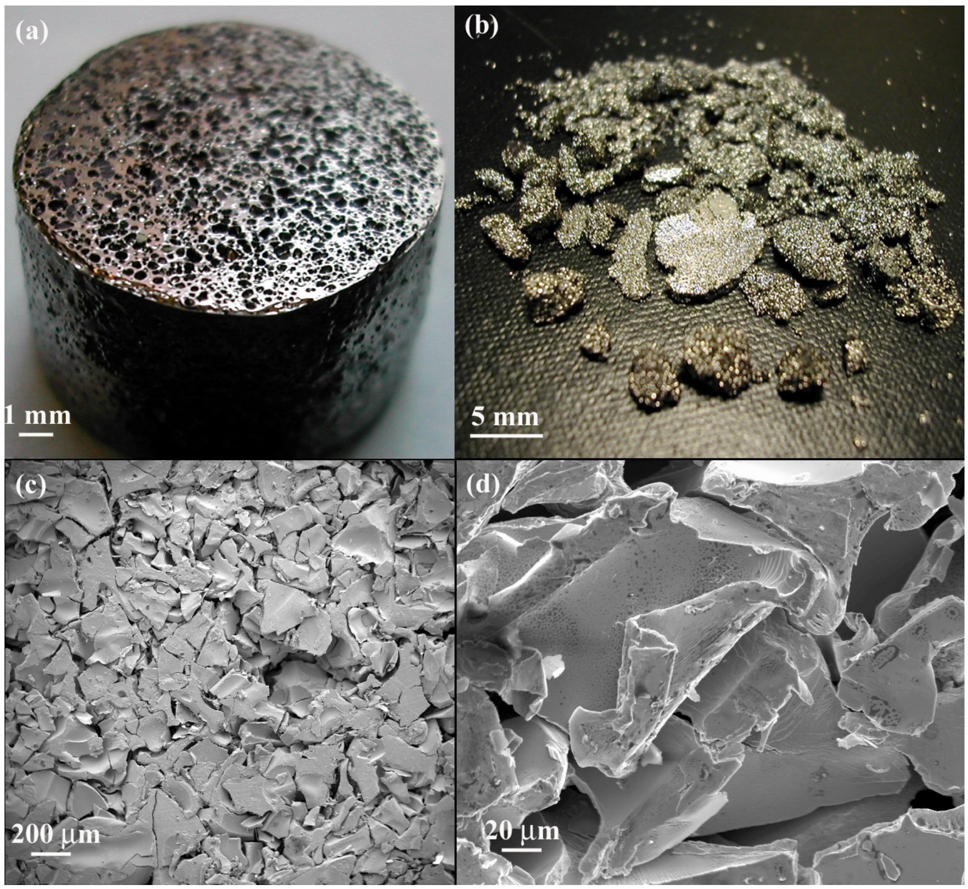

Figure 5.1: (a) Image of a foam specimen as prepared for dynamic compression. (b) Image of a foam specimen after dynamic compression showing several completely densified pieces among other crushed pieces. (c),(d) Electron micrographs of a completely densified piece of a dynamically compressed foam.

Data was reduced according to the well known equations relating the stresses and strains to the incident, reflected and transmitted strain signals [64]. Wave dispersion was also corrected, according to the guidelines of Lifshitz and Leber [65]. Finally, specimen equilibrium was carefully verified in each test by comparing the applied forces on each side of the specimen.

Results

The stress-strain response of foams loaded dynamically over a range of relative densities from 0.13 to 0.60 with applied strain rates between 3000 and 3500 s^{-1} is presented in figure 5.2. The same general behavior is observed for all relative densities: a peak in stress is attained at approximately 0.02-0.03 strain, followed by relaxation to a rather constant stress plateau. Expectedly, as the relative density decreases, the Youngs modulus, yield stress, and plateau stress all decrease. After failure, the foam structure appears fairly fragmented. The fragments consist largely of undeformed fractured portions as well as portions that have been heavily deformed to full densification (figure 5.1(b)). Micrographs in figure 5.1(c) and (d) show one such fully densified portion from a fragmented foam specimen at low and high magnification. At high magnification (figure 5.1(d)), features including severely deformed cell walls and regions densely populated with shear bands can be seen, indicating that the struts yield plastically before or instead of fracturing. The existence of these plastically deformed features implies that plasticity may be the dominant mechanism of yielding during dynamic loading.

The quasi-static loading tests were performed over relative densities ranging between 0.22 and 0.65 and strain rates ranging between 10^{-3} and 10^{-4} s^{-1}. The post-yielding deformation behavior of such foams under quasi-static loading conditions has been studied extensively elsewhere [29, 35]. A typ-

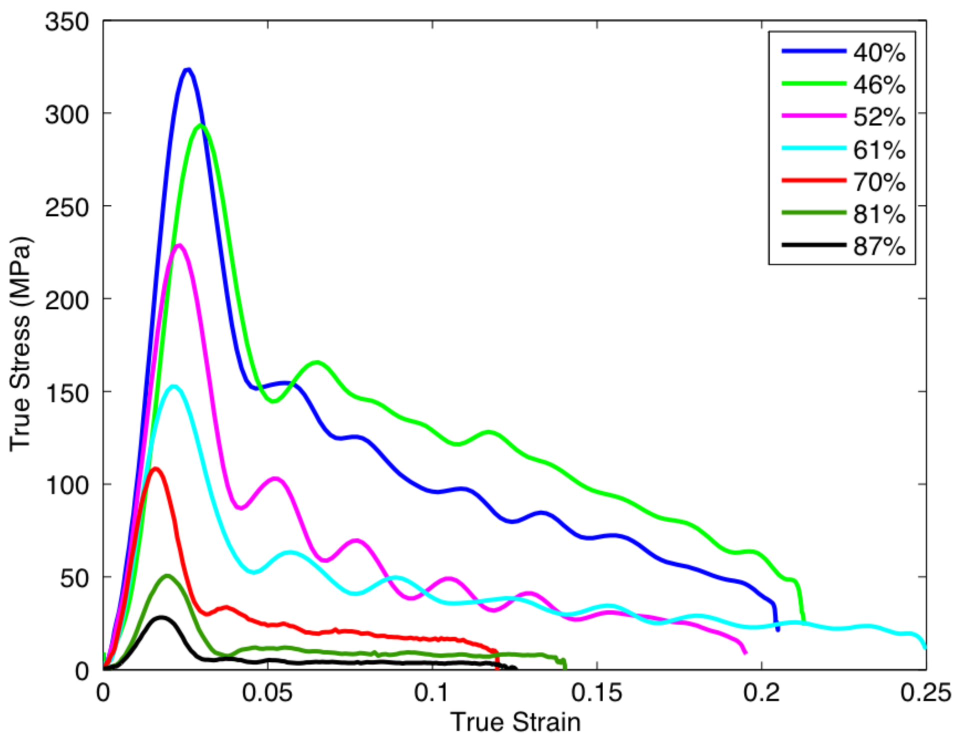

Figure 5.2: Dynamic stress-strain response of foams with varying relative densities (reported in percent porosity) under strain rates between 3000 s^{-1} and 3500 s^{-1}.

ical stress strain response of a 0.4 relative density foam deformed under a strain rate of 10^{-4} s^{-1} is shown in figure 5.3. In the same plot, we also present the stress-strain response of a specimen of equivalent relative density deformed dynamically under a strain rate of 3500 s^{-1}. The post-yielding deformation behavior for the two strain rates present some notable similarities: yielding is followed by a stress drop of about 40% towards a rough stress plateau that extends beyond 10% strain. Another interesting similarity is that yield strength for the two strain rates is nearly identical. Since monolithic amorphous metals are known to be strain-rate insensitive [13, 63], one would reasonably expect the yield strength of an amorphous metal foam to remain unchanged when the strain rate is increased from quasi-static to dynamic loading conditions. Surprisingly, the foam yield strength appears to remain unchanged with strain rate only at 40% relative density, while at other relative densities the two applied strain rates result in very different foam yield strengths.

Discussion and Conclusions

In figure 5.4 we plot the relative yield strength (foam yield strength, σ^*, normalized by the yield strength of the parent solid, σ_y, known to be 1630 MPa) [29] as a function of the relative density, ρ^*/ρ_s, for the foams tested dynamically along with those tested quasi-statically. As seen in the plot, the relative strength versus relative density data for the low and high strain rate tests fall on two distinct curves with different slopes. The two slopes in the relative strength/relative density relations point to two distinct mechanisms of yielding. That is, even though the post-yielding behavior for low and high strain rate deformation appears to be qualitatively similar (figure 5.3), the actual yielding transition (i.e., the elastic to plastic transition) appears to be

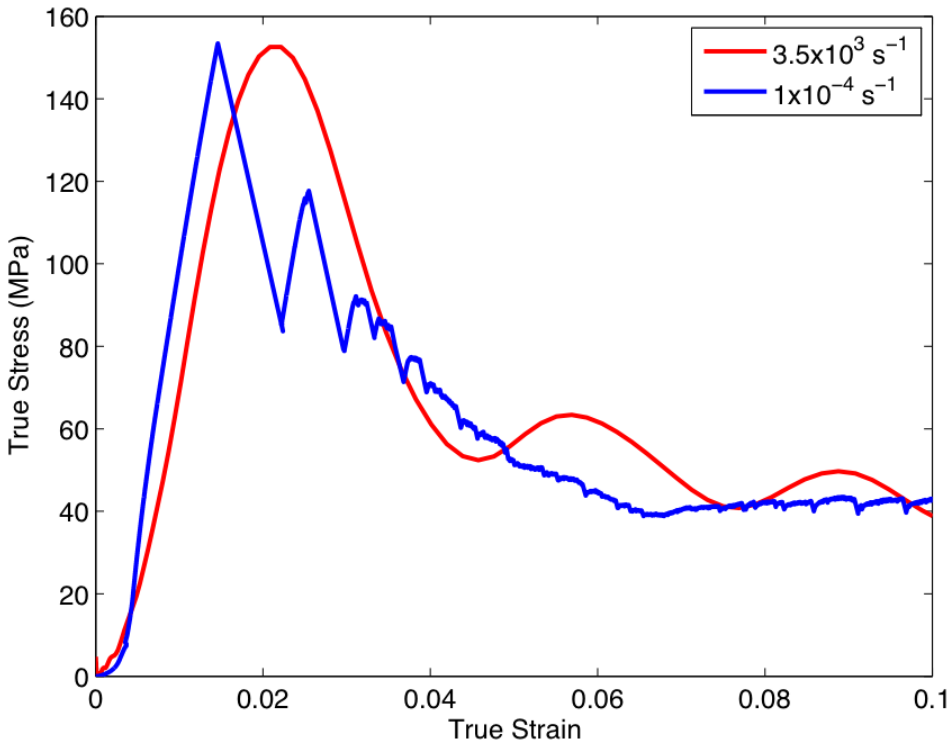

Figure 5.3: A comparison of the stress-strain response of two 60% porosity foams under applied strain rates of 3500 s^{-1} and $1{\times}10^{-4}$ s^{-1}.

fundamentally different for the two strain rate regimes. Power law fits give an exponent of 2.38 for the quasi-static data and 1.65 for the dynamic data. According to the prominent work of Gibson and Ashby [24], strength/porosity relations characterized by a power exponent of $\sim$2 indicate a foam-yielding mechanism dominated by elastic buckling, while power exponents of $\sim$1.5 indicate predominantly plastic yielding.

A recent in situ x-ray microtomography study [35] identified that the yielding transition of highly stochastic metallic glass foams loaded quasi-statically is indeed controlled by elastic buckling. Specifically, that study showed that yielding in such foams initiates by Eulerian buckling of high-aspect-ratio membranes distributed randomly throughout the cellular structure, and evolves by percolation of these elastic instabilities toward a non-catastrophic collapse event. The elastic yielding of quasi-statically loaded foams is therefore consistent with the relative strength/relative density power exponent of 2.38. On the other hand, the severe plastic deformation observed in the fragments of dynamically loaded foams [Fig 5.1(c) and (d)] points to a yielding mechanism dominated by plasticity, and the strength/porosity power exponent of 1.65 is also consistent with this assessment.

The strength/porosity correlations along with the observation of the yielding and failure transitions suggest that metallic glass foams with essentially self-similar cellular structures yield by distinctly different mechanisms when loaded under drastically different strain rates. Conventional metal foams, such as aluminum foams, demonstrate higher yield strengths under dynamic strain rates at a given relative density, but no apparent shift in the slope of the strength/porosity correlation (inset in figure 5.4) [66]. The higher yield strengths attained under dynamic loading can be attributed to the strain-rate sensitivity of monolithic aluminum. However the power exponent remains essentially constant with strain rate (1.4 for static and 1.6 for dynamic) which

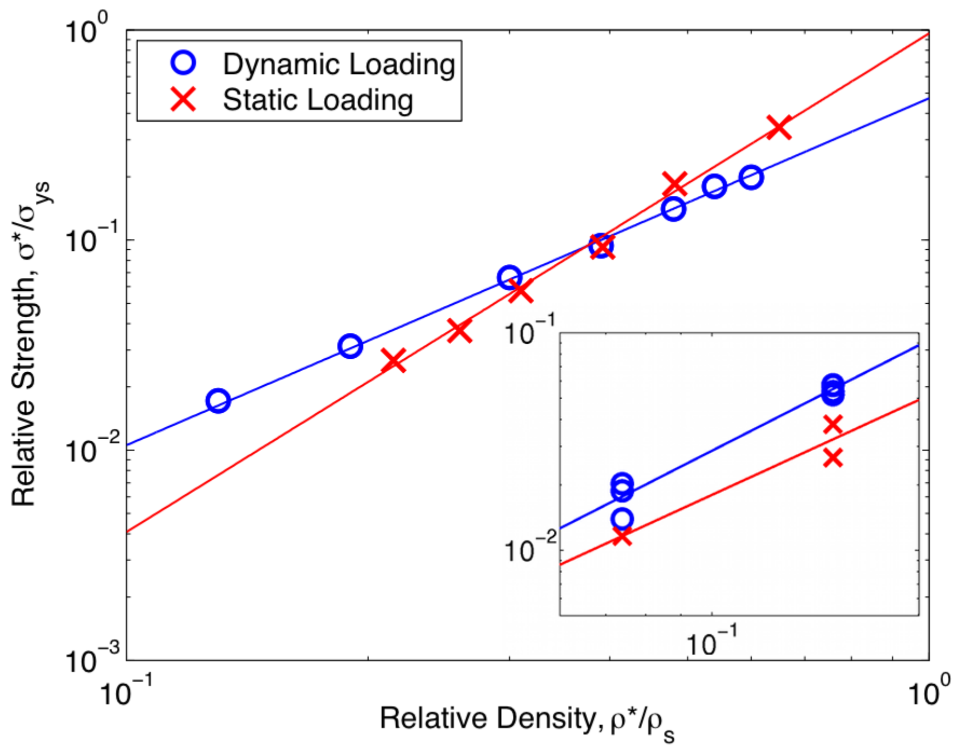

Figure 5.4: Relative strength as a function of relative density for foams tested under low and high applied strain rates. The inset shows a comparison between quasi-static ($\sim 10^{-4}$ s^{-1}) and dynamic (10^3 s^{-1}) compression of aluminum foams (Ref. [66]). Solid lines are power-law fits to the data.

suggests that the dominant yielding mechanism, which for those foams is identified to be plasticity, remains unchanged on going from quasi-static to dynamic strain rates.

The strain-rate-induced change in the foam yielding mechanism from elastic buckling to plastic yielding for the metallic glass foams investigated here can be understood by examining the mechanisms and the characteristic timescales that control them. Because of the high elastic limit of metallic glasses, a metallic glass column would generally be less stable against buckling for a given aspect ratio than a crystalline metal column. Specifically, the critical aspect ratio that determines a columns stability against elastic buckling is given by $n\pi/\sqrt{\varepsilon_{el}}$, where ε_{el} is the elastic strain limit of the material, and the index n depends on the end constraints and ranges between 1/2 and 2 [67]. Using $\varepsilon_{el} = 0.02$ for a metallic glass column, one can estimate the critical aspect ratio to range between 20 and 40. In contrast, the critical aspect ratio for an aluminum column with $\varepsilon_{el} = 0.005$ can be estimated to range between 40 and 80. This propensity for elastic buckling forms the basis for the elastic yielding tendency of these foams, as high-aspect-ratio membranes distributed randomly throughout the cellular structure tend to buckle at critical stresses below the plastic yield stress giving rise to a global elastic yielding response [35].

As known from the work of Lindberg and Florence [68], the transient buckling response of a column to dynamic pulsed load is characterized by a timescale associated with the speed of sound in the column material. When a column is submitted to a pulsed load for duration shorter than this timescale, or equivalently, when the rate of deformation of a column exceeds this characteristic rate, the column may yield plastically before it has time to buckle elastically. To examine this concept as it pertains to this study, we define two timescales: the timescale associated with the speed of sound in the material, $\tau_{wave} = l/c$, where l is a characteristic length scale and c is the speed of sound in the material, and the timescale associated with the rate of elastic deformation, $\tau_{load} = \varepsilon_{el}/\dot{\varepsilon}$, where ε_{el} is the elastic strain limit of the material and $\dot{\varepsilon}$ is the applied strain rate. If $\tau_{load} \gg \tau_{wave}$, as in quasi-static loading, buckling would be enabled. If $\tau_{load} \geq \tau_{wave}$, as in a dynamic compression test, buckling would be suppressed. For a metallic glass membrane typical of the foams in the current study, l is on the order of the average cell size, which can be taken to be about 1 mm, $c = \sqrt{E_s/\rho_s} \approx 3200$ m/s, where $E_s \approx$100 GPa and $\rho_s \approx 10^4$ kg/m^3 are the Youngs modulus and density of $Pd_{43}Ni_{10}Cu_{27}P_{20}$

glass, respectively, and $\varepsilon_{el} \approx 0.02$. This data give $\tau_{wave} = 3 \times 10^{-7}$ s. For a quasi-static loading test with $\dot{\varepsilon} = 10^{-4}$ s^{-1} we have $\tau_{load} = 200$ s $\gg \tau_{wave}$, which implies that a stress wave could travel across the membrane many times before the plastic yield strength is reached, therefore elastic buckling would occur. For a dynamic loading test with $\dot{\varepsilon} = 10^{4}$ s^{-1} however we have $\tau_{load} = 2 \times 10^{-6}$ s $\cong \tau_{wave}$, which implies that a membrane would reach plastic yielding as soon as the stress wave begins propagating through it, and therefore elastic buckling would be avoided.

In conclusion, microscopic analysis along with strength/porosity relations for stochastic metallic glass foams loaded dynamically reveal that dynamic yielding is controlled predominantly by plasticity, unlike quasi-static foam yielding, which is known to be dominated by elastic buckling. The strain-rate induced shift in the foam yielding mechanism is attributed to the convergence of the timescale characterizing dynamic loading and the timescale associated with sound-wave propagation across structural membranes, which thereby suppresses elastic buckling.

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