Mechanical Performance of Amorphous Metallic Cellular Structures

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Abstract

Metallic glass and metallic glass matrix composites are excellent candidates for application in cellular structures because of their outstanding plastic yield strengths and their ability to deform plastically prior to fracture. The mechanical performance of metallic-glass and metallic-glass-matrix-composite honeycomb structures are discussed, and their strength and energy absorption capabilities examined in quasi-static compression tests for both in-plane and out-of-plane loading. These structures exhibit strengths and energy absorption that well exceed the performance of similar structures made from crystalline metals. The strength and energy absorption capabilities of amorphous metal foams produced by a powder metallurgy process are also examined, showing that foams produced by this method can be highly porous and are able to inherit the strength of the parent metallic glass and absorb large amounts of energy. The mechanical properties of a highly stochastic set of foams are examined at low and high strain rates. It is observed that upon a drastic increase in strain rate, the dominant mechanism of yielding for these foams undergoes a change from elastic buckling to plastic yielding. This mechanism change is thought to be the result of the rate of the mechanical test approaching or even eclipsing the speed of elastic waves in the material.

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Chapter 1

Introduction

Bulk Metallic Glasses

The first metallic glass, discovered in 1960 as a result of studies on rapidly cooled metals, was a $Si_{25}Au_{75}$ alloy that was rapidly quenched against a spinning copper wheel at $\sim 10^6$ K/s into flakes about 10 μm thick, which were found to be unstable as an amorphous structure at room temperature for times longer than a few hours [1]. Since this discovery, amorphous metals have been the subject of a great deal of research that has resulted in a multitude of glass-forming alloys in many alloy systems including, but not limited to, the Pd-Si-based ternaries studied by Chen and Turnbull [2], the Zr-Al-(Ni-Cu) and Pd-Ni-Cu-P alloys of the Inoue group [3, 4], and the Zr-Ti-based beryllium-containing (Vitreloy) alloys developed by the Johnson group of Caltech [5, 6].

A glass is a solid that has been formed without undergoing the discontinuous solidification of crystallization. The solidification of a glass happens continuously as the liquid becomes more and more viscous until the liquid is essentially solid, that is the liquid is viscous enough that the time required for a rearrangement of the positions of the atoms in the liquid is significantly greater than the laboratory timescale [7]. This transition from liquid to glass is called the glass transition and happens at a temperature called the glass transition temperature, T_g, defined as the temperature at which the liquid has a viscosity of 10^{12} Pa-s. At this viscosity (for $T = T_g$), Vitreloy 1, an exemplary glass-forming alloy has a structural relaxation time of ~100 s [8] which means that it would take about 2 minutes to observe any flow with no externally applied stress. At lower and lower temperatures, the relaxation time would continue to increase making the alloy appear essentially solid. A glass can be formed as long as this transition can happen without crystallization of the liquid.

The rate at which a liquid must be cooled in order to successfully avoid crystallization can be inferred from time-temperature-transformation diagram (TTT) for crystallization. The lowest cooling rate at which the nose of the TTT is still avoided is called the critical cooling rate. The lowest critical cooling rate ever measured for an amorphous metal is 0.005 K/s, which was measured in dispersed droplets of $Pd_{43}Ni_{10}Cu_{27}P_{20}$ [9]. The critical cooling rate for bulk $Pd_{43}Ni_{10}Cu_{27}P_{20}$ has been measured to be 0.09 K/s [10]. Low critical cooling rates allow a glass-forming alloy to be formed with large dimensions. An alloy with similar composition, $Pd_{40}Ni_{10}Cu_{30}P_{20}$, has been formed into fully amorphous specimens with minimum dimension as large as 72 mm [11]. The development of many bulk glass-forming alloys (those that can be formed >1 mm thick) has allowed for thorough study of the properties of these materials.

Metallic glasses have a unique set of mechanical properties including high strength and elasticity, broadly varying toughness, and lack of ductility [12]. For example, bulk metallic glasses have remarkably high yield strengths, σ_y, (up to ~2 GPa) [13], large elastic limits (near 2% strain), a wide range of fracture toughness, K_c, (ranging from 2 MPa$\sqrt{m}$ to nearly 100 MPa$\sqrt{m}$) [14], and effectively zero ductility in tension at room temperature. Metallic glasses can, however, show some plasticity in more stable loading conditions like compression [15] and bending [16]. Bending is an interesting loading configuration for metallic glass because it combines compression, where uniaxially tested metallic glasses can show plasticity, and tension, where they show none. When a plate of metallic glass is bent so that the surface stresses exceed the yield stress of the material, shear bands will form at the surface. The shear band spacing and the distance the shear bands will travel toward the neutral axis is determined by the thickness and curvature of the sample. In thinner samples (equal to or thinner than the plastic zone size, $d = K_c^2/(\pi\sigma_{ys}^2)$) the shear bands travel shorter distances and, therefore, have smaller offsets resulting in lower chance of a crack nucleating from a shear band, so a thin sample will yield plastically [16, 17].

These mechanical properties are the direct consequence of the amorphous structure of metallic glasses. Unlike crystalline metals, the atoms in an amorphous metal are arranged in a more or less randomly, that is, there is no long-range order so no line defects, like dislocations, are possible. In crystalline metals, dislocation motion is the main method of deformation, and plastic deformation increases the density of dislocations, which causes a macroscopic strain hardening. Because of this lack of crystalline order, dislocations are not present in metallic glasses, so metallic glasses have strengths closer to theoretical strength than any other bulk metals, but this also leaves no strain hardening mechanism. Metallic glasses actually exhibit strain softening at room temperature which results in inhomogeneous flow upon yielding which manifests itself as narrow regions of plastic deformation referred to as shear bands. When a specimen of metallic glass is loaded uniaxially, plastic deformation generally restricted to few shear bands, and the ultimate failure generally occurs along one dominant shear band oriented along a plane of maximum shear ∼45° to the axis of loading. When metallic glasses do exhibit plasticity, it is due to the formation of multiple shear bands [18].

Metallic glasses bridge the gap in toughness between ceramics and metals, and can exhibit very brittle or quite ductile behavior. Recently, much research has been focused on understanding the physics of metallic glasses and what makes some glasses less prone to brittle failure. In examining fracture toughness and fracture energy Lewandowski et al. realized that the intrinsic toughness of a metallic glass is related to Poisson's ratio, ν, for the material. A transition from low fracture energy to high fracture energy is observed as ν increases beyond $\sim$0.32 [14]. Attempts have been made to produce metallic glasses with high Poisson's ratio and, consequently, greater toughness and plasticity with varying degrees of success [9, 19, 20, 21]. Another method of toughening metallic glass is to produce a composite consisting of a metallic glass matrix and another (usually softer) interspersed phase. The most successful metallic glass matrix composites have been *in situ* composites made by precipitating a low shear modulus dendrite phase in the liquid alloy prior to quenching. These composites exhibit ductility in tension and very high toughness [22, 23].

As a result of the extraordinary mechanical properties and the recent breakthroughs in the toughening of metallic glasses, there is ongoing interest in the use of metallic glasses as engineering materials. Because of the remarkably high yield strengths and potential for high toughness, these materials are attractive candidates for use as the parent material in very strong cellular structures with high energy absorption capabilities.

Cellular Solids

Ranging from natural materials like wood, cork, and bone to advanced engineering materials like impact-absorbing car bumpers, heat exchangers, and lightweight building panels, cellular solids have many uses. Cellular solids can be fabricated in many different geometries which can be separated into two different categories: aperiodic structures, as in the case of foams, and periodic structures, like honeycombs and trusses. Each geometry lends a distinct set of properties to the structure. These materials have been thoroughly studied over the last three decades and their properties are fairly well understood [24, 25].

Engineered cellular solids are usually designed to meet the specific needs of an application. The cellular structures examined in this thesis are designed to be strong and light and capable of absorbing large amounts of energy. High strength structures with good energy absorbing capabilities should be made from a high strength parent material and should be designed so that the walls or struts of the structure can be loaded to the yield strength of the parent material without buckling elastically and the structures should maintain a considerable and constant stress level over a wide range of strain. In order to achieve this, the parent material should be able to undergo significant plastic deformation before fracture occurs. Elastic buckling is avoided by designing cell walls and struts to have slenderness smaller than a critical slenderness ratio for buckling. Brittle failure of metallic glass is avoided by producing struts and walls that are thinner than the plastic zone size of the parent material.

Chapters 2 and 3 of this thesis deal with the design, fabrication, and testing of honeycomb-like structures made from bulk metallic glass (BMG) and metallic glass matrix composites (MGMC), respectively. To date, periodic cellular structures made of metallic glass or its composites have not been seen in the literature. Periodic structures made from crystalline metals, on the other hand have been available commercially for several decades and their mechanical properties have been well characterized [26, 27]

The mechanical properties of cellular solids are determined by several factors including cellular geometry, the properties of the parent material and, in the case of the strength capabilities of a structure, the dominant yielding mechanism of the cellular elements, and follow general semi-empirical relationships of the type developed by Gibson and Ashby [24]:

$$\frac{\sigma^*}{X_s} \simeq C \left(\frac{\rho^*}{\rho_s} \right)^n , \tag{1.1}$$

where σ^* is the yield strength of the cellular solid, X_s is the relevant scaling property of the parent material, C is a scaling coefficient that comes from the geometry of the cells, and n is an exponent determined by the geometry of the structure and the mechanics of the cell walls. The measured properties of the cellular structures in this thesis will be compared to semi-empirical relationships of this type. This comparison with established correlations can show whether the cellular solid has inherited the desirable properties of the parent metallic glass. Further discussion of the origin of these relationships can be found in chapter 2.

Only recently have metallic glasses been utilized as the parent material for any cellular solid. Amorphous metal foams have been the subject of much study over the last 6 years, and can be made by several methods, including thermoplastic expansion after melting in the presence of a blowing agent [28], melting and casting in the presence of a high pressure gas [29], infiltration over a place-holding preform [30] or hollow spheres [31], and co-extrusion of powders with a fugitive phase followed by dissolution of that phase [32]. A honeycomb-like structure with unidirectional pores has also been produced by casting over then electrochemically etching away wires of a fugitive phase [33].

These amorphous metal foams have been shown to have a collection of mechanical properties not previously seen in porous materials. Amorphous metals with small amounts of porosity have been shown to have very high strengths and exhibit significantly more plasticity than monolithic specimens [29]. Structures with lower relative densities, specifically those comprised of struts thinner than the plastic zone size of the amorphous metal, have been found to be extremely deformable, as catastrophic failure due to global brittle fracture is effectively avoided [30, 34]. Highly stochastic foams comprised of struts with broadly varying thicknesses and aspect ratios have been shown to yield by elastic buckling [35]. When amorphous metal foams are produced with thin struts and uniform aspect ratios, they can avoid both brittle fracture and elastic buckling to yield plastically at rather low relative densities (<10%) [36]. Consequently, these foams are among the strongest foams ever seen.

Chapter 4 discusses the fabrication of high porosity amorphous metal foam by a powder metallurgy method and the excellent mechanical properties of these foams, and chapter 5 is concerned with the yielding mechanism of the aforementioned highly stochastic amorphous metal foams and the effect of strain rate on the yielding mechanism.

Chapter 6 summarizes the work in this thesis and proposes some interesting continuing research on the processing and mechanical performance of metallic glass and metallic glass matrix composite structures.