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Cell Wall Buckling Mediated Energy Absorption in Lotus-type Porous Copper

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The energy absorption characteristics of the lotus-type porous coppers at the strain rate of 10^{-3} s^{-1} to ~2400 s^{-1} were systematically investigated. Depending on the relative density and loading rate, the energy absorption capability of the tested samples varied from ~20 to ~85 MJ m^{-3}, while the energy absorption efficiency fluctuated around ~0.6. An energy absorption efficiency curve based approach was proposed for unambiguous identification of the plateau regime, which gave an extension of ~0.50 strain range for the presently investigated porous coppers. With detailed observations of cell wall morphologies at various deformation stages, it was suggested that buckling of cell walls was the dominant mechanism mediating the energy absorption in lotus-type porous coppers.

1. Introduction

Metal foams have been attracting plenty of research interests since emergence due to their unique mechanical properties, such as lightweight feature, large specific area, and great impact energy absorption[1–5]. Typical applications of these materials can be found in automobile, railway and aerospace industries[2–4]. Traditional metal foams, either in the closed-cell or open-cell form, normally consist of spherical or irregular pores randomly distributed over the entire metallic matrix, in which the stress concentration can easily build up surrounding pores, deteriorating the mechanical and energy absorption performance. This drawback is overcome by a new family of porous metals fabricated by the unidirectional solidification technique, which is composed of the metallic matrix and long columnar pores oriented in a specific direction and frequently referred to as the lotus-type porous material[6–9]. Compared to conventional metal foams, having pores arrayed directionally endows lotus-type porous materials with remarkable advantages, including improved strength and rigidity, feasibility for pore structure control, a wide range of pore diameters, and low fabrication cost[10–13]. Like most of other porous materials, lotus-type porous materials have a wide variety of potential applications, such as energy absorbers, filters, silencers, heat exchangers, electrolytic cells, and biomedical devices[10,14–17].

Energy absorption is a topic of constant interest in porous materials due to their crucial roles in impact energy dissipation applications, and their exceptional energy dissipation ability during crashing predominantly attributes to the extended plateau regime on a typical compressive stress–strain curve[18–20]. A series of studies by Tane and co-workers on lotus-type porous carbon steels and irons demonstrated the superiority of lotus-type porous metals in energy absorption over traditional metal foams owing to their unique deformation characteristics originating from anisotropy of the pore structure[21–25]. In fact, an almost ten times improvement in the energy absorption relative to the commercialized Alporas aluminum foam was observed in the lotus-type porous metals[21–24]. However, it was claimed in these works that appearance of the stress plateau regime and thus desired superior energy absorption is confined to the limited conditions, namely, high strain rate impacts at the low temperature (77 K) and compressions parallel to the longitudinal pore direction[21–25]. This, however, is somehow a misinterpretation of the nominal stress–strain data because of inappropriate assumption that the strain hardening feature at most room temperature tests is an indicative of the non-existence of the plateau regime[26]. Therefore, there is a call for proper approaches for characterizing the energy absorption of lotus-type porous materials. On the other hand, crush of a porous structure in actual applications could happen over a wide range of strain rates, and thus

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designing porous solids for energy applications requires a full characterization of the energy absorption over various strain rates. Naturally, strain rate sensitivity of the energy absorption becomes a central question in porous materials. Nevertheless, investigation on this in lotus-type porous materials is quite limited and isolated and consequently no solid conclusions could be reached, even though energy absorption characteristics of a few lotus-type porous metals were inspected at both quasi-static and dynamic conditions[21–25,27]. Due to shortage of such information, the feasibility of using lotus-type metals as energy absorbing materials in various loading conditions cannot thus be rationalized. In this sense, a sound conclusion is required with regard to the strain rate dependence of the energy absorption behavior of the lotus-type porous material.

In the present work, via uniaxially compressing the lotus-type porous coppers in the direction parallel to the longitudinal pores at various strain rates, we will first demonstrate a plausible approach to judge occurrence of the stress plateau regime, with which determination of the onset strain of the densification and hence a few important energy absorption parameters turn out to be straightforward. On top of that, the strain rate sensitivity and relative density dependence of the energy absorption properties of the lotus-type porous copper are thoroughly investigated. Finally, the deformation mechanisms that mediate the energy absorption of lotus-type porous coppers under quasi-static and dynamic conditions are discussed.

2. Experimental

The lotus-type porous copper was fabricated with a unidirectional casting apparatus, which consists of five major components: (i) a pressurized chamber; (ii) a graphite crucible with a hole at the bottom (for melt pouring) and an induction heating coil surrounded; (iii) a graphite stopper stick for preventing/allowing the melt to flow through the hole; (iv) a melt flow guiding funnel and alumina mold (50 mm in diameter and 170 mm in length) with a preheating induction coil around; and (v) a water-cooled copper chiller on the bottom, as schematically shown in Fig. 1. During the material fabrication, the apparatus is first vacuumized followed by being inflated with 0.1 MPa hydrogen gas (99.99%). The high purity copper (99.99%) was then melted in the crucible and maintained at 1150 °C for a half hour for saturated dissolution of the hydrogen into the molten copper. The alumina mold was preheated to 900 °C with a purpose of directing the bottom-to-top unidirectional solidification, and the temperatures of the molten copper and alumina mold were monitored by two sets of thermocouples. The lotus-type porous copper ingots with cylindrical pores aligned parallel to the solidification direction can then be formed through pouring the melt into the mold.

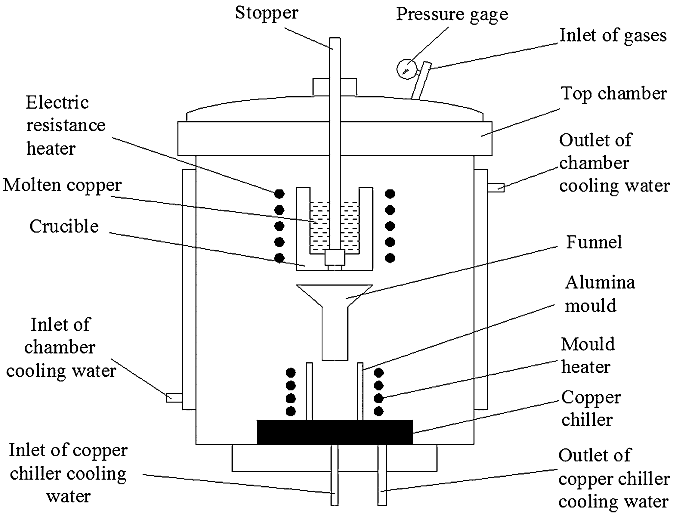

Fig. 1. Unidirectional casting apparatus for preparation of lotus-type porous coppers.

The lotus-type porous ingots were sliced into 10 mm × 10 mm × 10 mm cube specimens using electrical discharge machining (EDM), followed by ultrasonically cleaning to remove the dirty deposited in pores. The weight and volume of all samples were measured and the relative density was calculated according to

$$\rho_r = \frac{M/V}{\rho_s} \tag{1}$$

where M and V are the weight and volume of the sample, respectively, and ρ_s is the density of the pure copper. The pore morphology is imaged with the digital camera and statistically analyzed with the image processing software Image J.

The quasi-static compression tests (10^{-3} s^{-1}–10^{-1} s^{-1}), medium-strain-rate tests (1–60 s^{-1}), and dynamic tests (~800 s^{-1}–~2500 s^{-1}) were carried out on the MTS universal testing machine, thermal-mechanical simulator GLEEBLE-1500, and split Hopkinson pressure bar (SHPB), respectively, and all tests were performed at room temperature and a 80% deformation in all cases was attempted to be achieved in order to investigate the energy absorption properties at a wide strain range. Three different relative densities (0.35, 0.45, and 0.52) of lotus-type porous coppers were tested and each testing condition was repeated on at least three samples over which the compressive stress–strain data were averaged. In order to investigate the mechanisms mediating the energy absorption under both quasi-static and dynamic compressions, a number of samples with a relative density of 0.45 were selected to be compressed to ‘freeze’ at certain characteristic deformation stages, say, at the nominal strain of around 0.05, 0.15, 0.30, 0.45 and 0.70. These samples deformed to various degrees were then sliced from the mid-plane along the compressive direction, grounded/polished, and observed for deformation mechanisms of cell walls. Control of the deformation can be easily attained on the universal MTS testing machine by simply terminating the program at the desired magnitudes, but it is quite challenging under dynamic tests with the SHPB equipment because of its high impact speed nature. This was instead realized by adopting a so-called deformation freezing approach, namely, a series of stainless steel rings with different heights were attached to the transmission bar during tests to stop further impact of the striker bar on the sample. In such a way, the sample deformation can be controlled to the intended amounts. Such a technique is schematically illustrated in Fig. 2.

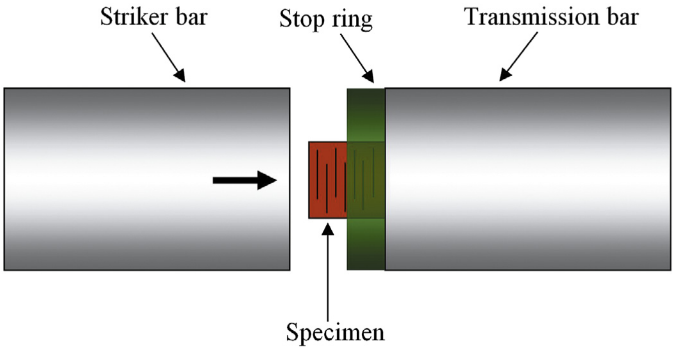

Fig. 2. Schematic of the deformation freezing approach for restricting deformation of porous copper specimens to designated amounts at dynamic tests.