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Effects of cell size on quasi-static compressive properties of Mg alloy foams

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ABSTRACT

Mg alloy foams with different cell sizes, fixed porosity, and uniform structure were prepared by direct foaming method. The microstructure characteristics and quasi-static compressive behaviors of the foams were investigated. The results showed that the pores in the foams were polygon with the porosity of 87%. Decreasing the cell size is beneficial to eliminating the big cell edges in the foams. The foams with smaller average cell size possess better deformation stability when being compressed. Decrease of the average cell size improves the strength of the foams by sharing the load with more and smaller cells; however too small average cell size can impair the strength because no enough metals hold the integrity of the new cell walls. The densification strain hardly changes with the varying average cell size and fixed porosity.

1. Introduction

Recently, metal foams have attracted much interest due to their unique structures (large specific surface for activator matrix and filter), mechanical properties (high specific strength for light weight tools) [1]. Many techniques have been developed to fabricate metal foams [2], and the relationship between structure parameters and properties was examined as well [1]. The reports mainly focused on Al and Al alloy foams [3]. At present, increasing interest in Mg and Mg alloy foams, the lighter metal foams, is taken.

Mg and Mg alloy foams show more potential for their smaller density (the lightest metal structural materials), biocompatibility (for skeletal repair [4]), electromagnetic properties (for electromagnetic shielding shells), and damping properties (for products used in vibrant environment). Many techniques were applied to Mg and Mg alloy foams preparation, and a few properties of these foams have been examined. The "lotus-type" Mg foam was made and characterized by Liu et al. [5] and Murakami et al. [6]. The thermo-conductibility of AZ91 foam, which was fabricated by injection method, was measured by Solórzano [7]. Wen et al. [8,9] studied the mechanical properties of the open cell pure Mg foam, which is fabricated by powder metallurgy method, and concluded that it can be used as biocompatible implant materials. Later, open cell Mg alloy foam was fabricated by Yamada et al. [10] with infiltrate technique. The effect of heat treatment on mechanical properties was also analyzed [11,12]. Direct foaming method, one of the most successful techniques applied to making close cell metal foams, has not be used to fabricate Mg and Mg alloy foams until 2007. Luo and Lin reported the application of direct foaming method to Mg and Mg alloy foam fabrication [13,14]. Their works indicate that fabrication of large volume Mg foam is possible. Yang studied the relationship between the porosity and compressive properties of pure Mg foam with the porosity in the range of 53–71% [15]. However, the details of the mechanical properties should be further examined in order to use this foam material in a large scale.

The cells in the metal foams can affect the mechanical properties greatly. According to Mu, the cell shape anisotropy has a significant effect on the plastic collapse stress and the energy absorption property in Al–Si foams [16]. He [17] found that the compressive properties improved with the smaller cell, but the opposite result was obtained by Yu et al. [18] in pure Al foams. Therefore, it is imperative to characterize the influence of cell size on Mg alloy foams.

The aim of this study was to explore the effects of cell size on the compressive properties of Mg alloy foams. The structure of Mg alloy foams and the deformation behaviors were characterized.

2. Materials and experiments

Mg alloy foams were prepared with a commercial magnesium alloy AZ91 by direct foaming method [13,14]. The AZ91D ingot was remelted in a resistance furnace. The melt was thicken by adding metal calcium and SiC particles. Then, the blowing agents were added into the composite melt accompanied by mechanical stirring. The melt was transferred into the foaming furnace. The melt was cooled in the air after foaming. Table 1 lists the composites of AZ91 alloy. The gas mixture of CO_2 and SF_6 was applied to prevent the melt from being oxidized.

Close cell Mg alloy foams with a diameter of 130 mm can be fabricated by this method. Mg alloy foams with different average

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Table 1
The chemical composition of AZ91 alloy, wt.%.

Al	Zn	Mn	Be	Fe	Cu	Si	Ni	Mg
8.89	0.62	0.32	0.0011	0.0017	0.0067	0.044	0.0005	Bal.

cell sizes (0.9, 1.0, 1.2, and 1.6 mm) were obtained by varying the blowing agent and foaming time.

Light optical microscopy and image analysis software were used to characterize the section of Mg alloy foams with different cell sizes. The porosity P was calculated according to:

$$P = (1 - \bar{\rho}) \times 100\% \tag{1}$$

where $\bar{\rho}$ was defined as the ratio of apparent density of Mg alloy foams ρ to the density of matrix material ρ_s.

Quasi-static compressive tests were performed to characterize the properties of as-foamed Mg alloy foams on an AG-100KNG compressive machine at the rate of 1.8 mm s^{-1} corresponding to strain rate of 10^{-3} s^{-1}. The Mg alloy foams were sectioned into cylindrical specimens (diameter: 29 mm, height: 30 mm) by electro discharge machining for compressive texts.

3. Results

3.1. Structure of Mg alloy foams

Typical structures of Mg alloy foams fabricated by direct foaming method were shown in Fig. 1. The porosity of Mg alloy foams is in the range of 60–90%, and the density is in the range of 0.2–0.8 g/cm^3 correspondingly. The average cell size varies between 0.5–2 mm, which is changed along with the particle size of blowing agent, the volume of the blowing agent, and the foaming time. Four kinds of Mg alloy foam samples for compressive test are shown in Fig. 2. We can see that the section shapes of cells are mainly polygon. Statistic results show that the average cell size is 0.9, 1.0, 1.2 and 1.6 mm, respectively. The porosity calculated according to Eq. (1) is 87% for all four kinds of samples. It can be seen that the melt has a trend to enrich at the cell edge which is surrounded by more than two cells, as shown by the arrows in Fig. 2. This trend will be weakened as the average cell size is decreased. The cell wall thickness varies in the range of 20–50 μm (as shown in Fig. 3), and almost unchanged with the cell size.

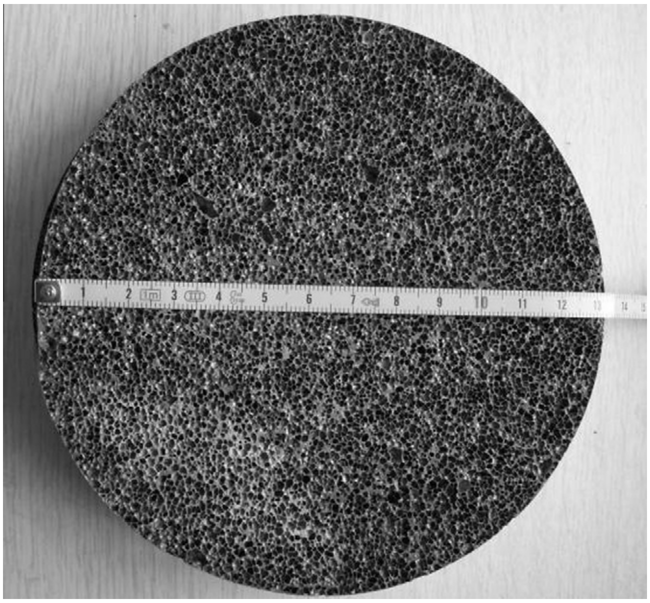

Fig. 1. Mg alloy foam fabricated by direct foaming method.

3.2. The character of compressive behaviors

The typical stress–strain curve of Mg alloy foams is shown in Fig. 4. The strain rate is 10^{-3} s^{-1} and the porosity is 81%. There are three stages in the stress–strain curve: linear deformation stage ($\varepsilon < \varepsilon_u$), yielding plateau stage ($\varepsilon_u < \varepsilon < \varepsilon_d$), and densification stage ($\varepsilon > \varepsilon_d$). An upper yielding point (A) and a lower yielding point (B), followed by a long (nominal strain usually rise up to 0.7 in this study) and fairly constant plateau stage, can be observed. Finally, the stress increases rapidly when the Mg alloy foam is densified. Here, the plateau stress σ_p is taken as the average compressive stress for compressive nominal strains within the range of 0.1–0.5. The densification point is defined as the last point where the slope is 13 MPa [19].

3.3. Effect of cell size on compressive properties

The stress–strain curves of Mg alloy foam with different cell sizes are shown in Fig. 5. We can see that with the decrease of cell size, the stress increases firstly and then decreases. Fig. 6 summarizes the stress figures and densification strain plotted against the cell size for the samples. The densification strain is almost unchanged with cell size when the porosity is fixed. Mg alloy foam with 1 mm average cell size possesses the best compressive properties in this particular study: 2.58 MPa upper yielding stress, 2.35 MPa plateau stress, and 4.29 MPa densification stress.

4. Discussion

4.1. Structure of Mg alloy foams

The cell shapes of metal foams, fabricated by direct foaming method, depend on the porosity. The spherical cells will change into polyhedron cell as the porosity is larger than 70%. The porosity of Mg alloy foam samples in this study is 87%, therefore the polyhedron shape cells could be observed, as shown in Fig. 2.

According to Banhart [20], the average thickness of the cell wall tends to maintain a certain value, and does not change with the relative density. As the cell size decreases, the cell number will increase to keep the porosity. The surface of cell wall increases accordingly, thus the metal in cell edge will form new cell walls.

The Mg alloy foams are characterized by smaller cell size and thinner cell walls. Average diameters of Mg alloy foams cells are mainly smaller than 2 mm, while the cells in Al foams are often larger than 3 mm [18,21]. Fig. 3 shows that the thickness of the Mg alloy foams cell wall is in the range of 20–50 μm, compared with 100–530 μm in Al foams [21–23]. The ratio of cell wall thickness to cell wall length is 0.1–0.18 in Al foams [24], however, it is only about 0.02 in Mg alloy foams. This discrepancy may be ascribed to the different physical and chemical properties and processing parameters, such as density, surface tension, viscosity, cooling rate, and holding time. The cell wall thickness is so small that larger cells will be more instable in foaming process. So the cell size of Mg alloy foams should be much smaller than that of Al foams to keep the cell from collapsing.

4.2. The character of compressive behaviors

When being compressed, the whole Mg alloy foams deform immediately, and the stress rises up to local peak stress. After that, one layer of weakest cells would be crushed. Then the stress decreases until the load head reaches the next cell layer and the process is repeated again. The stress–strain curve possesses a local peak stress and short linear deformation stage ($\varepsilon_u < 0.02$), which indicate that the Mg alloy foams is a typical kind of brittle foam [25]. This is attributed to the brittle matrix and the addition of