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Study on quasi-static compressive properties of aluminum foam-epoxy resin composite structures

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ABSTRACT

Closed cell aluminum foam (AF) has extensive application prospects due to its extended plateau stress region and high energy absorption capacity. As one of the most important manufacturing routes for aluminum foams, the gas injection method still does not guarantee an excellent energy absorption performance. In order to improve the energy absorption capacity while remaining the plateau region extended, epoxy resin (ER) was infiltrated into the aluminum foams in various composite forms. In this paper, different AF-ER composite structures were designed and their uniaxial quasi-static compressive behaviors were investigated. The experimental results indicate that the plateau stress and energy absorption capability of the AF-ER composite structures increase with increasing amount of epoxy resin. Additionally, both the stress fluctuation and the peak stress in the plateau region become insignificant, which is beneficial for energy absorption applications. The composite form is also confirmed to have great effect on the compressive property of the AF-ER composite structures. At last, the Young's modulus of the composite structure is theoretically deduced while the plateau stress and the energy absorption capacity are fitted with the composite parameters by considering the contribution of aluminum foam, epoxy resin and the reciprocity of these two materials. The present model is found to have good agreement with experimental data.

1. Introduction

Metal foams have gained increasing attention as a kind of new structural and functional material [1–3]. Among them, aluminum foams have been extensively used in engineering applications such as energy absorbers to resist external loads [4,5]. Those applications are attributed to plenty of closed cells inside the aluminum foam material. The porous cell morphology endows aluminum foam with many excellent characteristics such as high specific strength, low density and high energy absorption capacity, etc [6–8], which makes it a potential candidate for automobile bumpers. Common fabrication methods for aluminum foams include gas injection method [9], melt foaming method [10] and powder metallurgical method [11], etc. The aluminum foams prepared by gas injection method have the advantages of low cost [12], continuous production [13] and the possibility to prepare molded parts [14]. Therefore, they are the main concern in the present study.

In the compression process of aluminum foams, there are typically three stages in the stress–strain curve [15,16]: linear stage, plateau region and the densification stage. Aluminum foams prepared by melt foaming method, such as the Alporas type foam, are frequently studied. For instance, Zhou et al. [17] probed into the failure behaviors through uniaxial compression, uniaxial tensile and combined shear-tensile of aluminum foams by using the Alporas type foams. However, the aluminum foams prepared by gas injection method has a relatively low relative density, large cell size and thin cell wall compared to other preparation methods such as the melt foaming method or the powder metallurgical method [18]. Therefore, the value of the plateau stress and energy absorption capacity for aluminum foams prepared by gas injection method is in urgent need of increasing. In fact, the attempt to improve the property of the foamed material has a long history. Many novel composite structures have been proposed, which shed light upon the application of foamed materials.

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Alia et al. [19] reported the energy-absorbing characteristics of a kind of composite tube-reinforced foam structure and highlighted on the influence of tube diameter on the specific energy absorption. Wang et al. [20] studied the mechanical performance of an innovative sandwich panel with glass-fiber-reinforced polymer face sheets and a foam-web core. Their special attention has been paid on the four-point bending strength with experimental investigation and analytical modeling. Rajaneesh et al. [21] employed numerical approach to study the impact strength on open-face sandwich plates made of either ductile aluminum sheets or brittle carbon fiber reinforced plastic sheets. Moreover, Chang et al. [22] investigated the deformation behavior of sandwich materials from macro and micro-scale. The idea that lies in the above-mentioned composite structures can be summarized as a tough and strong skin surrounding a soft and lightweight core known as foams. This idea has been adopted in many occasions and illustrated by Gibson and Ashby [23] in detail. However, this paper explores otherwise to improve the performance of aluminum foams.

An alternative way to improve the compression property of aluminum foams is the introduction of polymers with different composite forms. In fact, the idea of utilizing the advantage of foams and polymers at the same time has fascinated many researchers. Agunsoye et al. [24] developed a kind of aluminum dross-epoxy resin composite material and studied the effects of aluminum dross filler on the wear behavior and thermal stability of epoxy resin system. Gong et al. [25] developed three kinds of metal porous polymer composite materials by infiltrating different polymers into porous aluminum structure, which allows for a better combination of mechanical and physical properties. Stöbener et al. [26] joined advanced pore morphology aluminum foam elements by 5–20wt.% polymer to obtain a kind of foam-polymer hybrid with attractive properties. In addition, Matthias et al. [27] summarized the definition and characteristics of hybrid foams. They treated hybrid foams as a kind of composite material that consists of two different interpenetrating or particulate-embedded foam-material classes. By taking advantage of these two kinds of materials, an enhanced multi-functionality can be expected. This idea has broadened the design of composite structure for aluminum foams because the foamed material does not necessarily locate in the center of the composite material with a tough layer of surface materials around.

Epoxy resin is one of the most important classes of polymer material with many excellent properties. Therefore, this study employs epoxy resin in the composite structure. More relevant investigations include the work by Kishimoto et al. [28,29]. They investigated the compressive mechanical properties of aluminum foam-epoxy and aluminum foam-polyurethane materials by measuring the deformation distributions using the digital image correlation method. However, their work is also focused on the Alporas type aluminum foams by melt foaming method. Therefore, a detailed analyze is still lacking for different aluminum foam types and different composite forms. As far as we know, there are few investigations on closed-cell aluminum foams prepared by gas injection method and epoxy resin composite structure. Therefore, this paper deals with several different kinds of composite structures including: (a) aluminum foams with epoxy resin side filling; (b) aluminum foams with epoxy resin cross filling through the center; and (c) aluminum foams with epoxy resin center-hole filling. Uniaxial compressive tests were conducted for these different designs. Stress-strain curves were recorded automatically while different failure modes were summarized for different composite structures.

Quantitative analysis of the compressive property of the AF-ER structure is needed because the analysis make it possible to investigate the influence of different parameters including the relative density of aluminum foams, the filling amount of epoxy resin and the composite form of these two materials. However, the composite structure of AF-ER material is very complex, which makes theoretical analysis very difficult. Models describing the plateau stress and energy absorption property of this composite structure are very rare. However, there exist many theoretical models that describe the elastic stage of two-phase materials. Voigt [30] proposed the first model describing the modulus of the composite material under a uniform strain assumption. A more widely-used assumption was proposed by Reuss, who reckon a uniform stress assumption [31]. Based on their assumptions, the Young's modulus of the AF-ER material is calculated theoretically.

There are no existing models describing the compression performance of AF-ER material as far as we know. Nevertheless, Lu et al. [32] did lots of work and explored the energy absorption of different porous composite structures and materials. Moreover, the deformation mechanism and mathematical description were provided by their research. Based on their research, a theoretical analysis is conducted on the deformation process and an equation predicting the plateau stress and the energy absorption capacity is proposed in this paper. The present model does not attempt to obtain a precise mathematical description but tries to consider the contribution of aluminum foams, epoxy resin and the reciprocity of these two materials. Experimental data were also collected to verify the present theory.

2. Materials and methods

2.1. Specimen preparation

Commercial A356 aluminum alloy (Al-7Si-0.3 Mg) was used as the matrix material with 10 vol.% Al_2O_3 particles (average size 10 μm) added. The chemical composition of A356 alloy was analyzed and shown in Table 1. The ceramic particles were first preheated to 400 °C for more than 2 h to improve the wettability between the particles and the melt [33]. Then the particles are spread into the A356 alloy which was heated to 700 °C in a stainless-steel crucible. In the spreading process, a graphite mixing propeller was used at the rate of 1300r/min to disperse the ceramic particles homogeneously into the melt. The stirring time is about 20 min in atmosphere. After that, the particle-contained melt was transferred to the stainless-steel foaming crucible.

Compressed air was introduced into the melt as the gas blows through an orifice submerged at the bottom of the crucible. The orifice was manufactured by laser drilling, the size of which is 0.15–0.6 mm. The bubbling gas was controlled at a constant flow rate and measured with a float flowmeter at room temperature. The gas flow rate and orifice size significantly affect the relative density of the foam, thus various samples with different relative densities were prepared. Generally, larger gas flow rate and larger orifice size is favorable for generating larger bubbles in the melt [34,35]. Therefore, the relative density of the aluminum foams decreases with gas flow rate and orifice size given that the cell wall thickness of aluminum foams by gas injection method has a minimum value, typically 50–100 μm [36]. Fig. 1 shows the influence of these two variables on the resulting relative density of the foams with four orifice sizes (0.15 mm, 0.2 mm, 0.3 mm and 0.6 mm) and three gas flow rates (0.25 L/min, 0.5 L/min, 1.0 L/min) used. It is noted that the temperature of the melt was maintained at about 660 °C.

During the gas blowing process, the foams accumulated on the melt surface. Then they are cooled and collected. Generally, two collecting methods are involved in the present study: (1) the direct pulling method to collect aluminum foam cylinders; (2) the roller aided pulling method to collect shaped slabs. For the first collecting