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Plastic deformation and compressive mechanical properties of hollow sphere aluminum foams produced by space holder technique

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ABSTRACT

In this study, experimental procedure and numerical methods were utilized to evaluate the effect of regular and irregular pore distribution as well as loading direction on compressive properties and deformation mechanism of hollow sphere aluminum foams. In order to study scaling laws, different volume fractions of the regular samples were produced and loaded in horizontal and vertical directions to address the loading conditions effects. For this purpose, expanded polystyrene (EPS) grains were expanded to a designed diameter size and positioned in different configurations. Compression test results showed higher elastic properties for irregular sample due to the thicker cell walls while energy absorption capability at high strains was found to be reduced due to the non-uniform deformation in comparison with regular foams. In regular samples, a nonlinear behavior in the elastic regime was observed since the imperfections during casting procedure. Furthermore, similar deformation mechanisms were found for the set of samples with similar pore configurations indicating the feasibility of controlling deformation mechanism by manipulating morphological characteristics. Finite element results well predicted deformation mechanism of structures and plastic properties of regular hollow sphere samples especially for plateau stress with less than 12% relative error.

1. Introduction

Development of metallic foams has attracted great consideration in the two past decades due to the unique and controllable properties of cellular materials in different scales [1]. Metal foams have made advancement in many areas owing to their superior multi-physics properties such as excellent strength to density ratio [2], desirable buckling behavior [3], vibration attenuation [4], great energy dissipation thanks to the plastic collapse [5], controllability on mechanical response [6], and high specific mechanical properties [7]. Application of metal foams in transportation industry is growing increasingly since safety implies use of low density materials with high energy absorption to reduce impact stresses [8]. Nowadays, many industries such as railway industry, filtration, heat exchangers, sound absorbers, building structure and insulation [9], and even sport equipment, enjoy the advantages of metal foams [10]. Hence, more sophisticated analysis methodologies are required to design metal foams for performance in multi-functional situations. For instance, in automotive industry, weight reducing in addition to increasing the ability of energy absorption is satisfied by increasing porosity of components, while it lead the strength and stiffness to decrease [11]. Such challenges implies a compromise between design parameters thorough suitable optimization methods.

It is intuitively obvious that many morphological parameters as well as sintering conditions play a prominent role in physical and mechanical characteristics of foams. Structure of cells, density of materials, porosity, pore size, and distribution affect mechanical strength and Young's modulus as well as shear modulus, ability of energy absorption, strain rate sensitivity, and fatigue behavior [12–14]. Moreover, deformation behavior of foams is directly influenced by pore architecture and specifies mechanical efficiency and elastic properties of foams.

Many approaches have been also developed for fabricating metal foams [15–20], Most of which lead to forming irregular pore architectures in foams, which are not mechanically as efficient and ideal as regular ones due to the lack of controllability and theoretical predictability on mechanical properties.

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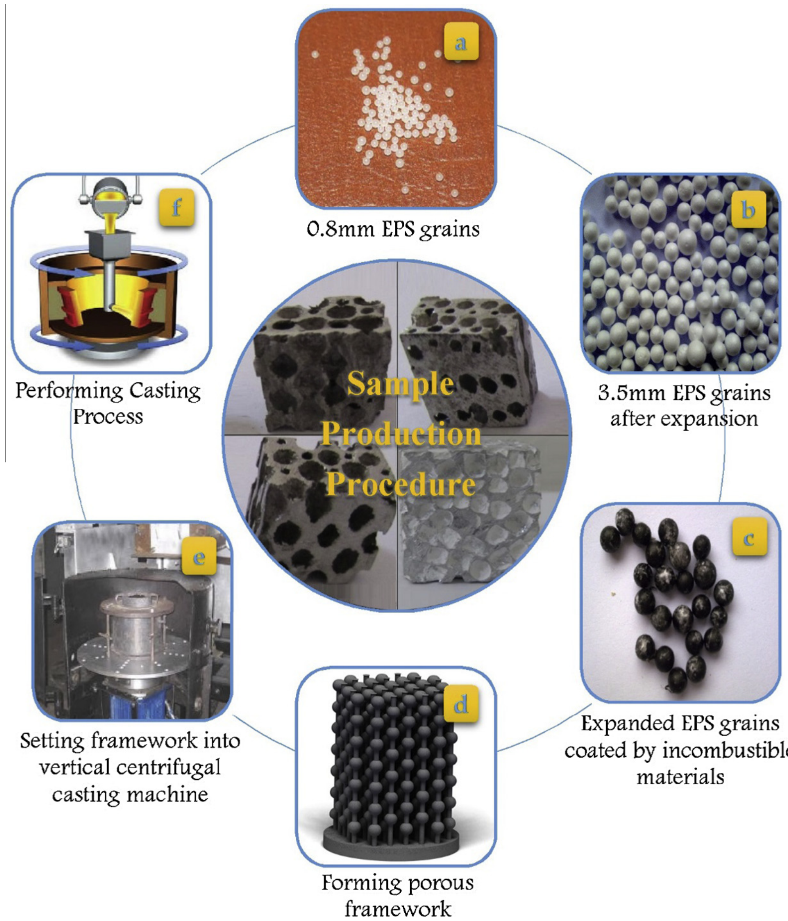

Fig. 1. Procedure of preparing aluminum foam samples using space holder technique through vertical centrifugal casting. (a) Initial EPS grains, (b) EPS grains after expansion procedure, (c) expanded EPS grains coated with an incombustible material, (d) framework preparation with the controlled pore distribution, (e) mini Foundry casting machine setup, and (f) schematic representation of centrifugal casting procedure.

Table 1
Morphological characterization of final aluminum foam samples produced by centrifugal casting procedure; regular samples with 20 mm cube length are labeled combining relative density and loading direction. The irregular sample with 30 ∗ 20 ∗ 20 mm dimensions was labeled as 35.0-IRR.

Sample label	Relative density	Loading direction	L (mm)	D (mm)	Pore configuration
27.3-V	0.273	Vertical	1	3.5	BCC
27.3-H	0.273	Horizontal	1	3.5	BCC
38.4-V	0.384	Vertical	2	3.5	BCC
38.4-H	0.384	Horizontal	2	3.5	BCC
50.0-V	0.500	Vertical	2	3.5	SC
50.0-H	0.500	Horizontal	2	3.5	SC
35.0-IRR	0.350	–	–	3.5	–

It is reported in the literature that spherical cell foams, named hollow sphere foams, have provided improved conditions for dynamic shock and energy absorption [15]. Mechanical properties of such structures are more predictable than those produced by other production methods. Hollow sphere foams are commonly fabricated by consolidating hollow spheres with the melt or by compacting the spheres through powder metallurgy [16–18]. In this area, Bafti and Habibolahzadeh [3] investigated the effect of cell shape, size, and relative density on the compressive behavior of aluminum foams produced by space holder technique utilizing Carbamide powder as the space route. They theoretically analyzed the constant values in scaling laws and relationships for densifications strain and plateau stress for metallic foams and concluded that spherical cells provided higher mechanical properties in the structure. Szyniszewski et al. [6] executed a comprehensive study on the mechanical characterization of hollow sphere steel foams in terms of compression and tension and investigated elastic and plastic parameters applying calibrated Deshpande-Fleck plasticity to mechanical simulations of steel foams. They finally claimed that such structures had high bending rigidity and energy dissipation potential. Moreover, Luong et al. [19] studied compressive failure mechanisms under diverse strain rates ranging to cover quasi-static and high strain rates for hollow sphere aluminum foams and reported higher compressive and plateau stress than ash cenosphere filled aluminum matrix syntactic foams. Ming et al. [20] assessed the tensional failure mode of hollow sphere filled syntactic epoxy-ceramic foams using experimental and numerical procedures. They found finite element results in good agreement with the experimental observations and reported the domination of brittle fracture mechanism under tensile load. Effect of particle clustering on failure mechanism was numerically studied by Ming et al. [21]. They stated that the elastic behavior of syntactic foams was insensitive to the degree of particle clustering and could considerably affect strength and failure modes.

Since the mechanical aspects of aluminum hollow sphere foams with regular pore architecture have been inadequately addressed, in this work, we investigated morphological parameters effect on compressive behavior of hollow sphere structures by controlling pore distribution in production procedure. In addition, effect of