Materials Science & Engineering A 734 (2018) 453–475

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Compression behavior of individual thin-walled metallic hollow spheres with patterned distributions of microporosity

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ARTICLE INFO

Keywords:
Compression testing
Failure mode
Finite element method
Metallic hollow sphere
Nanoindentation
Porous material

ABSTRACT

This paper presents an integrated experimental and computational study of the compression behavior of individual thin-walled metallic hollow spheres (MHS) with patterned distributions of microporosity. Quasi-static compression testing, including purely elastic loading, was conducted on two groups of individual MHS with two different sizes to examine the entire deformation process as well as the purely elastic response. Three-dimensional finite element modeling was then performed to investigate the effects of different microporosity distribution patterns on the MHS compression behavior and to understand the pertinent deformation and failure mechanisms. Results show that the Young's modulus and collapse stress of individual MHS with a uniform microporosity distribution decrease nonlinearly with porosity, which follows the same power-law functions developed for the porous wall material. For other patterned (i.e., vertical, horizontal, and random) distributions of microporosity involving localized weak wall sections, buckling commences at the weak sections, generating "buckling lines", followed by buckling failure along these adjacent or converged "buckling lines". Moreover, among the "buckling lines" generate some hinges that contribute to the increased load-bearing capability during the densification process. These findings can shed lights on the design, manufacturing, and modeling of individual MHS and MHS-based materials with specifically tailored engineering performance.

1. Introduction

Metallic hollow sphere (MHS) structures (MHSS) are becoming increasingly attractive for many applications ranging from aerospace materials (e.g., sandwich panels), to industrial functionalities (e.g., energy-absorbing and damping structures), and to medical replacements (e.g., biomedical artificial limbs) [1], mostly owing to their high strength and extremely low density. To date, several novel technologies have been developed that manufacture MHS with a wide range of diameters (D) and wall thickness (t), such as coating styro-foam using fluidized bed powder metallurgy or electrodeposition processes, and coreless methods using inert gas atomization of metallic alloys [2]. MHSS are typically made of numerous MHS attached together by sintering, soldering, or epoxy resin, among others, and the configuration and arrangement of spheres in MHSS can be divided into five subgroups: simple cubic (SC), body-centered cubic (BCC), face-centered cubic (FCC), hexagonal-closed packing (HCP), and random packing [3]. The majority of publications aims to understand the mechanical properties of MHSS by studying their compressive, tensile, fatigue, and dynamic behavior [4–10]. In general, the mechanical properties of MHSS are dominantly dictated by the characteristics of individual MHS, inter-sphere bonding, and packing configurations. Therefore, the mechanical behavior of individual MHS is of fundamental importance to the understanding of the mechanical performance of MHSS. However, the MHS are characterized by a high microporosity within the porous thin wall. As a result, the dependence of the mechanical (including elastic, plastic, collapsing, and buckling) behavior of individual MHS upon the porosity and its distribution is worth further investigation.

A number of experimental, numerical, and analytical studies have been reported on the quasi-static compression behavior of individual hollow spheres. Lim studied the deformation behavior of the 405 ferritic stainless steel hollow spheres (with D = 2 mm and t/D = 0.05) and found that the deformation process is significantly controlled by plastic bending and, upon densification, wall contacts [4]. Carlisle et al. experimentally measured and parametrically simulated the uniaxial compression behavior of carbon microballoons (D = 22 μm and a

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https://doi.org/10.1016/j.msea.2018.08.016
Received 2 May 2018; Received in revised form 18 July 2018; Accepted 6 August 2018
Available online 08 August 2018

relatively larger $t/D = \sim 0.06$–0.1) [11,12]. Gupta et al. extended the investigation of quasi-static compression of large hollow aluminum spheres (D = 40–125 mm with a mixed range of t/D = 0.002–0.03) to compression at high loading rates of up to 10 m/s [13–15]. Besides, several papers have reported the dynamic behavior of hollow spheres. Ruan et al. reported the crushing behavior of a single ping-pong ball compressed by point loading, rigid ball, rigid plate, rigid cap, and double rigid balls, as well as the one-dimensional (1D) and 2D load-deformation behavior compressed by rigid plates [6]; Dong et al. studied the collapse behavior of selected ping-pong ball arrays under different impact velocities using a split Hopkinson pressure bar (SHPB) system [16]; Li et al. conducted high loading-rate experiments and finite element modeling (FEM) to investigate the underlying deformation and failure mechanisms of thin-walled hollow nickel spheres [17]. On the other hand, these experimental, computational, and analytical studies focusing on the quasi-static or dynamic behavior of hollow spheres usually consider the thin wall as a nonporous and homogeneous material, especially in the FEM simulations. In reality, some thin-walled hollow spheres such as ping-pong balls have highly uniform sizes and shape but a very small discrepancy in wall thickness. However, the thin wall of most real manufactured MHS has a high to very high porosity due to their unique metallurgical manufacturing process. Moreover, most pores within the thin wall are irregular polygons in shape. In fact, the MHS thin wall is a kind of highly porous material. For porous materials, several approaches have been developed concerning the relationship between their mechanical properties and porosity. For example, Roberts and Garboczi et al. used FEM to study the influence of porosity and pore shape on the elastic properties of some porous ceramics, and established three types of models to assess the dependence of elastic modulus and Poisson's ratio on porosity: overlapping solid spheres, overlapping spherical pores, and overlapping ellipsoidal pores [18]; Song et al. conducted nanoindentation testing and synchrotron X-ray computed tomography (XCT) to characterize the mechanical properties and microstructure of porous MHS thin walls respectively, then used the real microstructure obtained by XCT to build the physical FEM models for simulation, and further developed the nonlinear relationships linking the Young's modulus and yield strength of the porous thin wall to its porosity, with the exact formulae for estimating the mechanical properties of the porous thin wall based on the real pore morphology and microstructure [19].

With regard to the research methods, in addition to experimental investigations, FEM has been widely used to simulate the macroscopic response of individual MHS and MHSS under quasi-static or dynamic compression [20,21], and even to probe the buckling and post-buckling behavior of thin-walled shells [22–24]. In these work, one of the basic assumptions is that the thin wall of MHS is a nonporous and homogenous material. However, the actual manufactured MHS always have such features as varied wall thickness and differently-sized micropores within the thin wall. In other words, there is a discrepancy between the ideal MHS considered in computational and analytical studies and the real manufactured ones used in practice. Therefore, it is necessary and important to understand the actual deformation and failure behavior of the manufactured MHS. One particular advantage of FEM modeling is that insights into the physical mechanisms underlying the phenomenological behavior of thin-walled MHS with different microporosities can be elucidated, and hence FEM can be used to investigate and analyze the compression process and failure of individual MHS with differently patterned distributions of microporosity, prior to the development of viable technologies for manufacturing MHS and MHSS with controlled microporosity and specifically tailored mechanical functionalities.

Although the deformation and failure process of ideal MHS with the so-assumed nonporous and homogeneous thin wall have been discussed in the literature, little effort has been made to study the properties of those manufactured ones with varied microporosity and wall thickness distributions. This paper aims to fill this gap with an integrated experimental and computational study: while experimental work mainly involves the quasi-static compression, including purely elastic loading, of manufactured individual MHS with real but unknown microporosity to understand their deformation process, computational work consists of FEM modeling to fully investigate the underlying mechanisms for quasi-static deformation and failure that make up the overall constitutive behavior of MHS with differently patterned distributions of microporosity. Results from the experimental measurements and FEM simulations will be compared and then exploited to assess the microporosity and its distribution of the manufactured MHS. Findings can expectedly advance the design and manufacturing of individual MHS and MHS-based foam materials as well as the modeling and prediction of their mechanical performance.

2. Materials and methods

2.1. Materials

The studied MHS, manufactured by the Fraunhofer Institute for Advanced Materials (Dresden, Germany), were selected from the same batch of samples studied by Song et al. [19]. The diameter, wall thickness, and wall porosity of these hollow spheres are slightly different from each another, and the two most common diameters are ~ 2 and ~ 3 mm with a wall thickness ranging from 0.01 to 0.04 mm. Interestingly, preliminary microscopic observations found that the MHS with relatively larger diameters have thinner walls (i.e., $D = \sim 3$ mm with an average t = 0.02 mm) than those smaller spheres (i.e., $D = \sim 2$ mm with an average t = 0.03 mm). The MHS wall is made of medium carbon steel with a Young's modulus of 207 GPa and a yield strength of 982 MPa, as measured by prior nanoindentation testing [19]. Images obtained by a scanning electron microscope (SEM, FEI Inc., Hillsboro, OR, USA) clearly reveal that the MHS wall possesses randomly distributed, multiscale pores with complex morphologies and pore sizes of 1–2 to ~ 50 μm (Fig. 1). Synchrotron XCT [19] indicates that the microporosity of the MHS wall varies from ~ 5% in some local sections to as high as ~ 42% for an entire cross-sectional surface (Fig. 2).

2.2. Quasi-static compression testing

To characterize the entire compression process of individual MHS, unidirectional, quasi-static compression testing was conducted on eight randomly selected MHS with carefully measured diameters (i.e., D = 2.905, 2.910, 2.945, 2.968, 1.987, 1.994, 2.009, 2.012 mm), which were divided into two subgroups based on their diameters: $D = \sim 2$ or ~ 3 mm. Each MHS was first cleaned with ethanol to remove dust and other potential contaminants on its surface, and then subjected to unidirectional compression testing between two smooth stainless steel platens in a GeoJac loading system (Trautwein Soil Testing Equipment, Inc., Houston, TX) at a displacement rate of 0.05 mm/min in the ambient laboratory environment (i.e., at a room temperature of ~ 25 °C). The nominal strain ε and nominal stress σ representing the measured engineering strain and stress are defined as the vertical deformation δ and load P normalized by the diameter and external cross-sectional area of the MHS, respectively, which are given as [25]:

$$\varepsilon = \frac{\delta}{D} \tag{1}$$

$$\sigma = \frac{P}{S} = \frac{4P}{\pi D^2} \tag{2}$$

where S is the external diameter-based overall cross-sectional area of the sphere.

Since the individual MHS was compressed unidirectionally (i.e., with 2 contacting points) without any lateral confinement, the horizontal deformation was not explicitly considered. Moreover, the horizontal deformation is nonuniform along the vertical direction, making it difficult to measure and quantify this parameter. Nevertheless, the