International Journal of Mechanical Sciences 52 (2010) 680–688

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Impact behaviour of hollow sphere agglomerates with density gradient

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ARTICLE INFO

Article history:
Received 20 January 2009
Received in revised form
27 October 2009
Accepted 17 November 2009
Available online 24 November 2009

Keywords:
Hollow spheres
SHPB
Impact testing
Cellular materials
Energy absorption

ABSTRACT

This paper presents a study on the influence of the density gradient profile on the mechanical response of graded polymeric hollow sphere agglomerates under impact loading. Quasi-static, standard split Hopkinson pressure bar (SHPB) tests as well as higher speed direct impact Hopkinson bar tests and Taylor tests are performed on such hollow sphere agglomerates with various density gradient profiles. It is found that the density gradient profile has a rather limited effect on the energy absorption capacity from those tests. It is because the testing velocity performed (<50 m/s) is rather small with respect to its average sound wave speed (around 500 m/s) and the equilibrium stress state can be reached rather quickly. The high impact tests allow to generate a non-equilibrium state condition and the influence of density profiles is clearly observed. Besides, in order to extend this study to the situation beyond our testing limitations, a numerical model is built on the basis of the experimental behaviour data. It confirms the important influence of the density gradient profile under a non-equilibrium stress state situation. This study shows that placing the hardest layer as the first impacted layer and the weakest layer as the last layer has some benefits in terms of maximum energy absorption with a minimum force level transmitted to the protected structures.

1. Introduction

Impact behaviour of cellular materials (honeycombs, foams, hollow sphere agglomerates, etc.) gain much scientific interest nowadays because of their worthy properties such as good specific resistances and high specific energy absorption capacities. For example, they can be employed as the core material of sandwich panels used to protect the cockpit against bird strikes or as the filling material in the hollow structures in a car to improve its energy absorption capacity [1,2].

Over the last decade, the idea of functionally graded materials (FGMs) was introduced in the materials sciences researches. The FGMs properties vary gradually within the material to optimize the global material function. Such FGMs structures can be easily found in nature. For example, bone possesses a gradient of densities in order to maximize the biological mechanical performance [3]. Nowadays, different manufacturing techniques have been explored to make artificial FGMs layers such as adhesive bonding, sintering, thermal spray, reactive infiltration, etc. [4,5]. FGMs properties have been thoroughly studied under quasi-static loading [6–8].

Important achievements have also been made in order to understand the mechanical response of FGMs submitted to stress waves and impact loading. A one-dimensional wave propagation model in FGMs is discussed by Bruck [9] to investigate the stress peak and the time delay in FGMs. Li et al. [10] have investigated the impulsive loading in the layered and graded structures using numerical models. They showed that the wave propagation consists of a complex coupling of elastic and viscoplastic part and the gradient profile plays an important role in the impact response. Gupta [11] has studied a functionally graded syntactic foam material (FGSF) and showed that a FGSF can support 60–75% compression without any significant loss in strength or failure, and the gradient profile of FGSF can control the compressive modulus, strength, and total energy absorption. Apetre et al. [12] studied the low-velocity impact response of sandwich beams with functionally graded core. It is shown that the grading core reduces the maximum strains corresponding to the maximum impact load. All those works, even mostly based on the theoretical analyses and the numerical simulations, show that the introduction of property gradient will largely modify the overall response of the designed FGM structures.

The present paper is aimed at the understanding of the role played by the density gradient in the overall protective capacity of the foam-like cellular materials under impact loading. The studied model materials, described in Section 2 are polymeric hollow sphere agglomerates of the same apparent density but with

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0020-7403/$ - see front matter
doi:10.1016/j.ijmecsci.2009.11.012

various density gradient profiles. A quite complete experimental study, performed using quasi-static test, standard SHPB tests, direct impact Hopkinson bar tests as well as Taylor impact tests, will be shown in Section 3. In the last section, a macroscopic numerical model is built and verified on the basis of experimental data. It allows for an extension of this study beyond our experimental limitation.

2. Mechanical behaviour of the hollow sphere agglomerates

2.1. Epoxy hollow spheres

The studied hollow sphere agglomerates have been manufactured and supplied by ATECA. The replication process is used to produce polyepoxide hollow spheres of specified external diameter around 2.5 mm. The thickness of hollow spheres is controlled in order to vary their density and the strength as a consequence.

Hollow sphere agglomerates can be made by bounding or sintering. Such hollow sphere agglomerates have not only good mechanical properties such as high specific energy absorption capacities and high specific strengths, but also excellent thermal and acoustic properties [13,14]. Previous studies in the open literature showed that the different packing of hollow spheres, for example body-centred cubic (BCC), face-centred cubic (FCC) and random packing, have different elastic modulus and initial yield strength [15–17]. However, the packing mode cannot be analyzed in the present work because the supplied hollow sphere agglomerates are randomly packed and joined by sintering. It is noted that such a packing mode corresponds to the industrial mass production acquirement. Under such packing mode, the density of supplied agglomerates of four different hollow spheres is given in Table 1.

2.2. Behaviour of randomly packed hollow sphere agglomerates of various densities

Quasi-static and dynamic tests are performed to obtain the nominal stress–strain relation of those randomly packed hollow spheres agglomerates. The geometry of the specimen used is a cylinder of 40 mm height and 60 mm diameter. Such a choice of specimen size limited the eventual size effect (around 15 times cell (sphere) size).

Quasi-static tests were performed on a hydraulic machine at constant compression velocity. The tests were performed at a loading speed of 0.01 mm/s that gives a nominal strain rate of 0.0025/s. The results are quite repeatable and the hollow sphere agglomerates demonstrated a classic foam-like material behaviour (Fig. 1). It is observed that there are three distinct phases: the linear elasticity, the plastic plateau and the densification regime. However, it is rather difficult to give an accurate value of Young's modulus and especially the plateau stress due to oscillations. Here the plateau stress is arbitrarily defined as average peak values in the early stage of plastic plateau regime. The identified Young's modulus and the plateau stress values as a function of the foam density are given in Table 2.

Table 1
Densities of the four types of hollow spheres.

Type name	C1	C2	C3	C4
Density (kg/m^3)	156	242	343	468

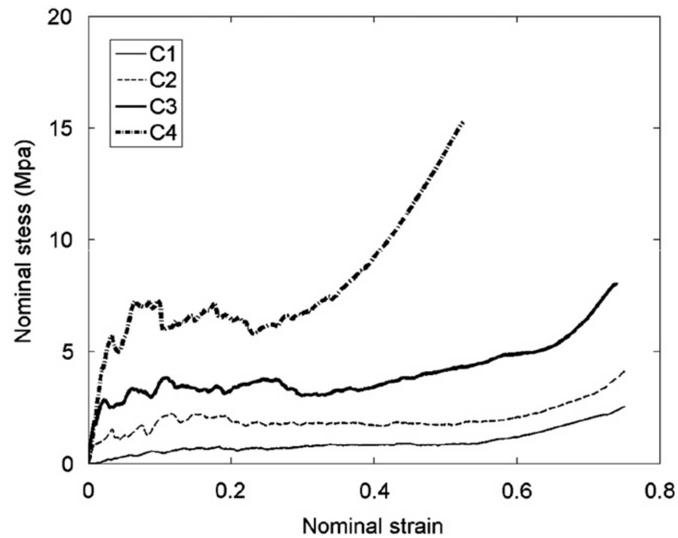

Fig. 1. Quasi-static compressive behaviour of hollow sphere agglomerates (without density gradient).

Table 2
Properties of four types of hollow spheres.

Type name	C1	C2	C3	C4
Young's modulus (MPa)	7	33	110	170
Plateau stress (MPa)	0.8	2.2	4.1	7.1

Dynamic tests at low impact velocity were performed with a split Hopkinson pressure bars (SHPB) apparatus which is a commonly used experimental technique to study the constitutive laws of materials at high strain rates [18]. The input and output bars (3 m long) are made from nylon material to ensure the impedance match [19]. The large diameter of the bars (62 mm) provides a correct representative specimen size compared to the size of the spheres. From SHPB test results, dynamic behaviour curves are plotted based on nominal quantities. Nominal stress is calculated as the measured output force divided by the initial cross-section of the specimen, as in the classical "2waves" method [19]. Nominal strain is the result of time integration of nominal strain rate. Strain rate is calculated as the relative measured velocity between output and input bar/specimen interfaces divided by the initial height of the specimen. Input and output force histories were checked and it validates the assumption of homogeneity in the specimen.

Fig. 2 shows the results for dynamic compression tests at an impact speed of 21 m/s. The theoretical nominal strain rate is about 525/s. The curves hardly show the densification regimes. It is due to the fact that the loading speed is not high enough to reach the densification regime within the 1.5 ms loading duration. The identified plateau stress values (defined as the peak value) as a function of the foam density are: 0.8 MPa (C1), 2.9 MPa (C2), 5.5 MPa (C3) and 8 MPa (C4).

A comparison between static and dynamic plateau stresses is plotted in Fig. 3. It shows that the studied materials have a rather small strain rate sensitivity of about 20%. Such rate sensitivities should be derived from the viscosity of the base material [20]. The spheres are quite brittle and the failure mode of the agglomerate is a successive breaking of sphere layers. There is then no supplementary rate sensitivity due to the structural effect such as the inertia effect because spheres are typically considered as Type I structure [21,22].