Powder Technology 268 (2014) 86–94

Contents lists available at ScienceDirect

Powder Technology

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

Size effect on the compression breakage strengths of glass particles

J. Huang, S. Xu *, H. Yi, S. Hu

University of Science and Technology of China, CAS Key Laboratory for Mechanical Behavior and Design of Materials, Hefei, Anhui, 230027, China

ARTICLE INFO

Article history:
Received 9 May 2014
Received in revised form 13 August 2014
Accepted 15 August 2014
Available online 25 August 2014

Keywords:
Particle breakage
Glass spheres
Breakage strength
Size effect

ABSTRACT

The quasi-static compression-breakage responses of the glass spheres with five different sizes (4–25 mm) are investigated. The breakage strength data are found to be highly scattered. Based on the Weibull model, a statistical approach is proposed to interpret the characteristics in the breakage strength of the glass particles. The Weibull stress concept is introduced to accurately define the breakage stress of the particles considering the effects of finite contact area and breakage modes. It is observed that the relationship between the cumulative survival probability of the particles and the breakage stress follows the Weibull distribution reasonably well. Moreover, the scaling law between the breakage strength and the particle size is consistent with the theoretical predication by the Weibull model. Finally, the energy consumption during the particle breakage process is discussed with a three-parameter Weibull distribution. The relationship of the characteristic energy and the particle size also follows a power law.

1. Introduction

Fracture and fragmentation of brittle materials are commonly encountered in engineering applications and of considerable scientific and industrial interest [1,2]. They are related to a wide range of phenomena, ranging from collisional evolution of large asteroids to disintegration of small agglomerates in the processing industries, e.g., pharmaceutical, food, and mining [3,4]. The breakage strength of single particles is a key parameter involved in several powder processing problems, including accidental breakage of the particles during transportation or storage [5], pulverization of catalytic particles [6], comminution efficiency of crushers and mills [7], and yielding transition of the particle beds under bulk compaction [8,9].

Extensive experimental studies have been dedicated to breakage properties of various brittle particles such as glass, ceramic, lime stone, and soil [10–12]. Two loading geometries are frequently used, i.e., the particle impact test and the symmetric compression test [11]. The particle impact tests have been widely employed to study the dynamic breakage process of brittle particles [10,13,14]. Effects of the impact velocity and the particle properties on the breakage modes and the fragmentation size distributions are discussed thoroughly. However, it is difficult to define and determine the breakage strength (the stress corresponding to failure) of the particles from the impact test. Only the threshold impact velocity which induces fragmentation is discussed concerning particle size or mineralogy [10,15]. Moreover, the inertial effects cannot be neglected under high-velocity impact. Compression test on spherical or disk-shaped particles is a common approach to measuring the tensile strength of brittle materials indirectly [16]. One can also use it to measure the breakage strength of brittle particles [5]. However, the definition of the stress for the spherical particles is still controversial [12]. The stress definition is critical for accurate measurements on the breakage strength and needs to be clarified from a physical basis. In addition, since particles of various sizes are handled in processing industries, the size effect on the breakage strength of the brittle particles should be investigated quantitatively.

Analytical solutions to the stress distributions inside an isotropic sphere subject to symmetric compression have been derived based on the Hertzian contact mechanics [2,17]. The theoretical stress distribution calculations suggest that along the compression axis, tensile stress develops in the circumferential direction, which may induce meridian cracks and consequently splitting of the sphere. This was observed for concrete [18] and plaster [2] spheres. Thus, the bulk crushing strengths of these spheres can represent the tensile strength of the constituent materials. However, the breakage modes of glass particles are much more complex [10,14]. Hertzian ring cracks are observed around the contact area and the failure planes are not necessarily meridian [14]. Moreover, the stress distributions and the breakage modes of the sphere are sensitive to the contact area between the sphere and the wall. When the contact area becomes comparable to the cross-sectional area of the sphere, the surface tensile stress exceeds the bulk tensile stress [17] and the surface cracks may dominate the fragmentation of the sphere [19]. However, the effects of the finite contact area on the breakage strength of the brittle particles have not been fully investigated.

* Corresponding author at: School of Engineering and Science, University of Science and Technology of China, Hefei, Anhui 230027, China. Tel.: +86 551 63601249; fax: +86 551 63606459.

E-mail address: slxu99@ustc.edu.cn (S. Xu).

http://dx.doi.org/10.1016/j.powtec.2014.08.037
0032-5910/

Many experiments have shown that the breakage strengths of brittle particles, though of the same size and morphology, vary in a considerable range due to the random distribution and evolvement of the micro-defects [13,19]. Therefore, sufficient number of samples should be tested to obtain an effective breakage strength from a statistical point of view. The Weibull statistics [20] is usually utilized to interpret the scattering data points. A two- or three-parameter Weibull distribution is used to fit the relationship between the breakage strengths and the survival probability [19]. The breakage strength distributions of several brittle particles (e.g., ceramic particles [21], soil particles [12], and rock aggregates [19]) are found to follow the Weibull distribution. The Weibull modulus, which characterizes the scatter of the breakage strengths of ceramic particles, is much bigger than those of the rock and soil particles. Moreover, some researchers found that the particle size dependence of the breakage strengths is consistent with the theoretical prediction (power law) by the Weibull model [12], but some did not [19]. The uncritical use of the Weibull distribution to fit the strength data of the brittle particles has been questioned [21]. McDowell and Amon [12] proposed that three assumptions should be cautiously considered when applying the Weibull distribution: (a) the loading geometries of all particles are similar; (b) particles are subject to bulk fracture; and (c) the contact radius is negligible compared to the particle size. The effectiveness of these assumptions should be examined and some modifications may need to be included in the commonly used Weibull model.

In the present work, the quasi-static compression-breakage properties of the glass spheres with five different sizes are investigated with the material test system 809 (MTS809). The compression force and displacement curves can be obtained from MTS809. The fragmentation process of the spheres is captured with the high-speed photography system. The size effect on the breakage strengths of the glass particles is discussed based on the Weibull model.

2. Experimental materials and setups

The K9 glass spheres are used as the experimental material. The spherical morphology eliminates the complications caused by the irregular shapes of real particles. K9 glass is widely used as an optical material and its fracture behavior is important for the manufacture of K9 optics. The bulk density of the K9 glass under normal conditions is 2.52×10^3 g/m^3. The chemical composition is SiO_2 (69.13%), B_2O_3 (10.75%), K_2O (6.29%), Na_2O (10.40%), As_2O_3 (0.36%), and BaO (3.07%) [22]. Spheres of five different sizes are used to investigate the size effect on the breakage strengths of the glass particles. The means and standard deviations of the sphere diameters calculated from 30 samples are 4.36 ± 0.08 mm, 8.02 ± 0.19 mm, 15.77 ± 0.19 mm, 19.78 ± 0.15 mm, and 24.70 ± 0.22 mm, respectively. The standard deviations are much smaller than the means, indicating that the spheres are of good uniformity in size.

The experimental setups are presented in Fig. 1. Fig. 1a shows the compression setups, i.e., the material test system (MTS809) and the high-speed photography system. All the compression tests are performed with the MTS809 at a constant loading velocity of 0.002 mm/s, which is sufficiently low to make the inertial effects negligible. The high-speed camera is used to capture the catastrophic breakage process of the glass spheres. A steel box with three transparent PMMA windows is used to gather the fragmentation debris of the glass spheres and protect the operator and the camera in case of debris splash. The enlarged graph of the loading cell is shown in Fig. 1b. Two steel blocks ($\Phi 14.5 \times 10$ mm) are stuck to the compression platens to avoid any damage to the platens. The glass sphere is sandwiched between the blocks with a thin layer of petrolatum in between to reduce friction. Upon loading, the lower platen compresses the sphere from the bottom up at a loading velocity of 0.002 mm/s while the upper platen is fixed. The loading stops when the sphere undergoes a catastrophic failure and the axial stress exhibits a sharp decrease from the maximum load. The axial force is measured by the force sensor embedded in the upper platen. The axial displacement, i.e., the displacement of the lower platen, is measured by the displacement sensor embedded in the lower platen. However, the axial displacement cannot be taken directly as the deformation of the sphere since it contains the deformation of the loading frame. Therefore, a compression test without a sphere between the blocks is performed to a maximum load of 60 kN. In this case, the axial displacement actually represents the deformation of the loading frame.

3. Experimental results and discussions

3.1. Compression responses

For each kind of glass spheres about 30 samples are tested to provide sufficient data for the subsequent statistical analyses of the breakage strengths of glass materials. The choice of this number of tests was based on the work of McDowell [23]. He proposed a statistical way to estimate the accuracy on the sample mean and standard deviation within specified confidence limits. He examined the specific case of a Weibull distribution of particle strengths (which is exactly the topic of this work) and concluded that for a Weibull modulus of 3 or greater (valid for glass [24]), 30 tests are adequate to accurately measure the mean particle strength.

The typical compression curves of the spheres with three different sizes, i.e., Φ4.18 mm, Φ15.71 mm and Φ25.03 mm, are presented in Fig. 2a, b and c, respectively. In the figure, "Corrected" means that the axial displacement is corrected to give the real deformation of the

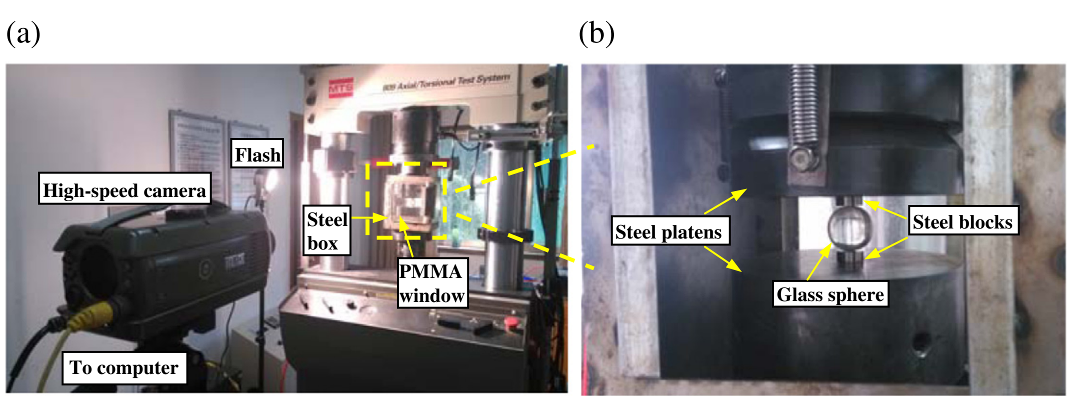

Fig. 1. (a) The MTS809 compression setup and the high-speed photography system. (b) The enlarged graph of the loading cell.