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Dynamic fracture behavior of single and contacting Poly(methyl methacrylate) particles

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ABSTRACT

Fracture behaviors of single, two, and multiple contacting spherical Poly(methyl methacrylate) (PMMA) particles were recorded using high speed synchrotron X-ray phase contrast imaging. A miniaturized Kolsky bar setup was used to apply dynamic compressive loading on the PMMA particles. In both single and two particle experiments, cracking initiated near the center of the particles and propagated towards the contacts. The crack bifurcated near the contact points for single particle experiments, thus forming conical fragments. The crack bifurcation and subsequent conical fragment formation was observed only at the particle-particle contact for two particle experiments. The particles were observed to fracture in hemispherical fragments normal to the contact plane in the multi-particle experiments. The observed failure mechanisms strongly suggest that the maximum tensile stress near the center of the particle is the critical parameter governing fracture of the particles. Furthermore, the compressive stress under the contact areas led to the bifurcation and subsequent conical fragment formation.

1. Introduction

Particulate materials are an important part of the modern industrial world; ranging from sand aggregates in concrete to solid dosage pills in pharmaceuticals. Breakage of solid particles during manufacturing, processing, handling, transportation, and usage is an important issue for efficient use of these particulate materials. The particle breakage can be intentional or undesirable depending on the process and application. Different comminution techniques have been developed for the purpose of intentional particle size reduction including impact jet milling and ball milling [1,2]. A better understanding of particle fracture mechanisms will help in increasing the efficiency of the comminution processes. On the other hand, fracture of particles during transportation or storage degrades the quality of the final product. The resulting fragments can cause erosive wear problems for the containers and transportation devices. The erosive wear can be a significant hazard for various kinds of coatings applied on the containers and other devices. Furthermore, the small fragments can cause adverse health effects, including silicosis and lung cancer [3,4]. In efforts to control particle breakage in a desirable manner, a better understanding of the particle fracture behavior is essential.

Poly-methyl methacrylate (PMMA) is a widely available material that is commonly chosen as a model material for the study of polymer particle failures. The failure mechanisms of PMMA under compression and impact loading have been reported previously [5–10]. It is suggested that the impact fracture of individual spheres initiates as plastic deformation in the conical region of material under the impact site leading to tensile hoop stresses, which in turn initiate cracks on the meridian planes [8]. Such meridional cracking has also been demonstrated by Okuda and Choi for the PMMA particles [10]. Chaudhri observed that the planar meridional cracks initiated near the contact area which fractured the particle, but did not penetrate the conical shapes near the contact [7]. Furthermore, the fracture mechanisms of PMMA spheres were observed to change as the impact velocity was

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increased, wherein the predominant cracking mechanism changed from radial cracks with circumferential cracks to splitting median cracks as the impact velocity was increased from 40 m/s to 80 m/s [6]. The particles were observed to fracture in small unidentifiable fragments when the velocity was increased above 115 m/s [6]. Two different failure modes: chipping and fragmentation were observed for impacts of small PMMA cubes, depending on the velocity and the impact orientation [5].

The observed cracking behavior of the PMMA particles will be helpful in numerical modeling of polymer and plastic particle fracture, specifically when using discrete element methods. Various researchers have proposed different techniques for replacing the fractured particles with fragments for modeling the granular systems that are susceptible to particle fracture [11–13]. The fragment replacement techniques include replacing the original particles with two spherical fragments with same mass [14], two equal sized clumps [15], one sphere with smaller radius with several fine particles added for mass conservation [16], 14 spherical fragments with different sizes [17,18,20] spherical fragments in an Apollonian packing [19]. The experimental results from this study may be used to guide the particle replacement techniques for PMMA particles in numerical simulations. Further, the recorded mechanical quantities such as force-displacement response and experimental observations of the fracture mechanisms will be useful in validating other numerical models including bonded particle models [20,21] and the finite element models [22].

Although, previous studies have reported the fracture mechanisms for single particles under compression and impact, the effects of inter particle contacts on fracture have not been studied. This paper examines the effects of contact conditions on the fracture behavior of PMMA particles under controlled dynamic compression.

2. Materials and methods

Commercially available solid PMMA particles (Engineering Laboratories Inc., Oakland, NJ) of diameters around 1600 μm were used for the single and two particle experiments. Particles of diameter around 800 μm were used for the multi-particle experiments to ensure that maximum number of particles could be visualized in the X-ray window. The particles were transparent and did not show any visible surface flaws. For each experiment, requisite numbers of particles were selected from a large collection of particles. The sizes of the particles were selected based on the ease of availability and the size limit imposed by the X-ray window.

Three different particle arrangements were investigated in this study: Single particle, two contacting particles, and multiple particles in a planar hexagonal packing scheme. A schematic of the particle arrangements with the holders is presented in the Fig. 1. For single particle experiments, the particle was constrained in an aluminum holder and compressed between two steel pins, as demonstrated in Fig. 1(a). For two particle experiments, the particles were constrained in a similar fixture, and a steel pin was used to compress the particles against the base of the aluminum housing, as shown in Fig. 1(b). For multi-particle experiments, 17 particles in a planar hexagonal packing arrangement were sandwiched between two 1.0 mm thick PMMA plates separated by a 0.84 mm thick steel plate. A 5.1 mm wide channel was machined in the steel plate and the particles were placed in this channel. A 5.1 mm wide flat faced steel plate was used to compress the particles against the back of the machined channel. A schematic of the particle arrangement for the multi-particle experiments is presented in Fig. 1(c).

A modified Kolsky bar setup was used to apply a controlled compressive loading and high speed synchrotron X-ray Phase Contrast Imaging (PCI) was used to record the in-situ fracture mechanisms of the particles. This experimental method has been used to study the failure mechanisms of various materials including concrete [23], sand particles [24], and high performance fibers [25]. More details of the experimental procedure are provided elsewhere [26,27]. The schematic of the experimental setup is presented in Fig. 2.

Polychromatic, high intensity X-ray PCI measurements were performed at beamline 32-ID-B, Advanced Photon Source (APS), Argonne National Laboratory. The fundamental energy of the X-ray beam used in this study with the undulator gap set to 11 mm peaked at 23.6 keV. The size of the X-ray beam on the sample was $2560 \times 1600\ \mu m^2$. The X-ray flux on the sample was 4×10^{16} - photons/s. X-ray PCI employs the change in the phase of the X-rays as they pass through the sample containing materials with different refractive indices, which in turn provides greater edge contrast that is beneficial for visualizing cracks in materials [28,29]. In the current study, inline propagation-based X-ray PCI technique was used [28]. A single crystal $Lu_3Al_5O_{12}$:Ce scintillator (dimensions: 10 mm × 10 mm × 100 μm) was used to convert the propagated X-ray signal to visible light wavelengths. The converted visible light images were recorded using an ultra-high speed camera (Shimadzu Hyper Vision HPV-X2, Tokyo, Japan). The temporal resolution of the recorded images was 500 ns (frame rate = 2,000,000 frames per second). The corresponding exposure time for each high speed image was 200 ns. The spatial resolution of the imaging system was measured to be 6.4 μm/pixel and the frame size was 100,000 pixels (400 × 250 pixels).

The dynamic compression loading was generated by a Kolsky bar apparatus, which is commonly used to characterize the material behavior at high strain rates (10^2–$10^5\ s^{-1}$) [30,31]. For the current experiments, a miniature compression Kolsky bar apparatus was used [26,27]. The Kolsky bar was composed of a striker bar (Ø = 12.7 mm, length = 305 mm) and an incident bar (Ø = 12.7 mm, length = 1372 mm), both manufactured from a high strength steel alloy. The transmission bar in the conventional Kolsky bar apparatus was replaced with a load cell (Kistler 9212, Winterhur, Switzerland) mounted on a heavy aluminum backstop due to space constraints in the APS X-ray experimental hutch. Two semi-conductor strain gauges (Kyowa KSP-2-1K-E4, Chofu, Japan) were attached diametrically to the surface of the incident bar and were connected in a half Wheatstone bridge configuration. The strain gauge assembly was used to record both the incident and reflected pulses. The load cell was used to record the force response of particles at the back end. Both the strain gauge signal and load signal were synchronized and collected via an oscilloscope (Tektronix DPO7104C, Beaverton, OR). The velocity at the bar end was calculated from the recorded strain signals using Eq. (1).

$$v(t) = C_B(\epsilon_i(t) - \epsilon_r(t)) \tag{1}$$

where C_B represents the elastic wave velocity in the bar. ε_i and ε_r represent the incident and reflected strain values respectively. The bar end displacement was then calculated using Eq. (2).

$$d(t) = \int_0^t v(\tau)d\tau \tag{2}$$

Note that τ symbol is used as the dummy variable in the definite integral in Eq. (2). For two particle experiments, Eq. (2) was used to measure the displacement of the compressing pin for two particle experiments. However, the back pin was observed to displace significantly for the single particle experiments. Hence, Eq. (2) did not provide accurate measurement of deformation of the particle. The relative displacement between the pins for single particle experiments was measured from the recorded high speed images. The calculated or measured displacement was