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SHEAR LOCALIZATION IN HIGH-STRAIN-RATE DEFORMATION OF GRANULAR ALUMINA

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Abstract—Dynamic deformation of densified granular alumina of two different particle sizes was investigated by the radial symmetric collapse of a thick-walled cylinder. The densified granular alumina was used to model the flow in ballistic impact and penetration of fragmented ceramic armor. Shear localization was a well developed deformation mode at an overall radial strain of ~0.2–0.4 and strain rate of $10^4\,s^{-1}$. The following qualitative features of shear bands were established:

- Shear bands have clear boundaries and their thickness does not depend on the initial particle size and has a typical value ~10 μm.
- The structure of the shear bands was dependent on initial particle size, suggesting differences in the mechanisms of flow. For the ~4 μm alumina, comminution (break-up) and softening of particles were observed. For the ~0.4 μm particles, a peculiar structure consisting of a central crack with two lateral cracks was formed.
- Distributions of shear bands and displacement magnitudes were dependent on initial particle size.

The observed differences in powder behavior are associated with different mechanisms of powder repacking. For large particles (~4 μm), additional hardening resulting from microfracture and subsequent repacking of different size particles in the powder takes place. The small-sized (~0.4 μm) ceramic does not go through the particle fracturing stage and the hardening is due to "classical" repacking.

1. INTRODUCTION

Ballistic impact of ceramic armor generates a range of phenomena that are still poorly understood. Shockey *et al.* [1] performed recovery experiments, which clearly show the different regimes of damage observed. Viechnicki [2] divided the levels of damage into three classes: a comminuted zone produced by shock waves; radial cracks produced by the expanding stress wave; and cracks generated by the reflection of the compressive pulses at the back surface of the armor plate. In the comminuted zone, the high-amplitude shock waves create stresses that exceed the strength of the ceramic. It is, as a result, finely divided into fragments. This comminuted (or finely fragmented) region is extremely important in the overall penetration mechanism, since it has to be ejected from the target in order for penetration to proceed. Mescall [3] postulated the existence of this region, based on hydrocode computations; experimental studies have confirmed its existence. Meyers [4] reviewed these mechanisms. The ejection of the comminuted, or "Mescall" zone, from the target requires large deformations of the granular material. The objective of this paper is to report results of experiments especially designed to subject dense and fragmented ceramics to large "plastic" deformation at high strain rates, representing in a realistic manner the behavior of the ceramic adjacent to a penetrator. The fragmented ceramic was modeled by precompacted alumina powder.

Shear localization is an important deformation mode in the quasi-static mechanical response of granular materials; it has been widely investigated both from an analytical and experimental point-of-view [5–16]. Rudnicki and Rice [5] developed a general formulation for shear localization in pressure-sensitive dilatant materials, of which granular materials are a special case. There are no reports, to the authors' knowledge, on shear localization under high-strain-rate loading of granular materials.

2. EXPERIMENTAL PROCEDURE

Alumina powders with two particle sizes were used in this investigation. These Al_2O_3 powders had a purity level of 99.97% and contained trace amounts of Na, Si, Ca, Ga, Fe, Mg, Ti and Zn. The powders

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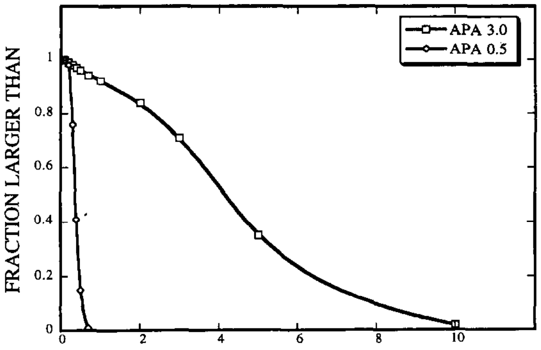

Fig. 1. Cumulative particle size distribution for CERALOX alumina.

were donated by CERALOX and have two designations:

(a) APA 3.0—median particle size: 4.17 μm; surface area: 1.5 m^2/g;
(b) APA 0.5—median particle size: 0.37 μm; surface area: 8.9 m^2/g.

The particle size distributions are given in Fig. 1. The two materials will be denoted "small" (or ~0.4 μm) and "large" (or ~4 μm) in the subsequent discussion.

The densification and deformation of the aluminas were carried out using the axial collapse of a thick-walled-cylinder within which the powder was placed. This thick-walled-cylinder method had been successfully used previously for research on solid [17] and porous materials [18, 19]. The experimental configuration [18, 19] used to generate controlled and prescribed shear localization in porous samples is shown in Fig. 2. The process has two stages: (a) densification of the powder [Fig. 2(a)]; (b) deformation of the densified powder [Fig. 2(b)]. The alumina powder with a density of 1.5 g/cm^3 (~38% of the theoretical value) was initially placed in a tubular cavity between a central copper rod (diameter 16 mm) and an outer copper tube (inner diameter 20 mm and outer diameter 31 mm). An explosive [explosive 1, mixture of ammonite and sand in 3:1 volume ratio, Fig. 2(a)] with a low detonation velocity (3.2 km/s) was used to densify this mixture to a density of 3.35 g/cm^3 (~84% of the theoretical value of 3.98 g/cm^3). Detonation was initiated at the top of the charge and propagated along the cylinder axis. Only small initiation sites of shear localization (Fig. 3) were observed after this stage because the overall plastic deformation is sufficiently small (final diameter of inner surface of driving copper cylinder, r_{10}, is equal to 17.9 mm). This stage produced mainly densification of the powder. The small step (marked by an arrow) seen in the copper container is indicative of the initiation of shear localization.

A cylindrical hole with 11 mm diameter was drilled along the longitudinal axis of the copper rod and this composite cylinder was collapsed by the detonation of a second cylindrical explosive charge [explosive 2 (ammonite), Fig. 2(b)] with a detonation velocity of 4.2–4.4 km/s, an initial density of 1 g/cm^3, and an outer diameter of 60 mm. This second explosive event produced significant plastic deformation in the densified porous layer which was highly localized in shear bands and not homogeneously distributed [Fig. 2(c)]. It is worthwhile mentioning that shear localization during explosive compaction of ceramic powders in the cylinder geometry was observed by Prummer [20].

3. RESULTS AND DISCUSSION

The general view of the collapsed ceramic cylinders is shown in Fig. 4. Profuse shear localization can be

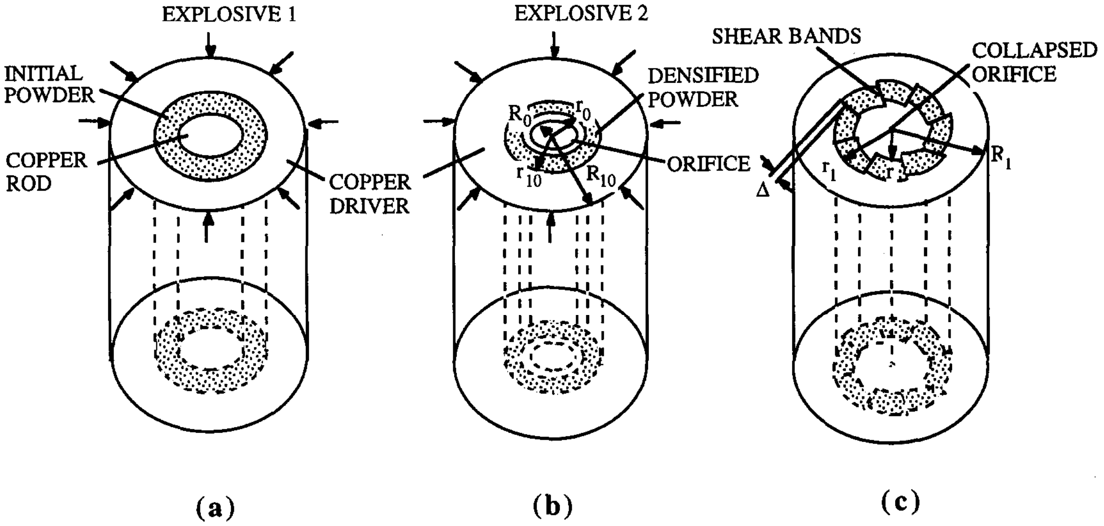

Fig. 2. Experimental set-up for densification and plastic deformation of ceramic: (a) configuration for densification; (b) configuration for deformation of densified alumina (notice axial orifice that enables large plastic strains in copper containers); (c) final configuration with schematic representation of shear localization.