Shock Deformation of Coarse Grain Alumina above HEL

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Abstract. Asymmetric shock recovery experiments with a two stage gas gun were conducted on a 10 μm grain size alumina at 6.5 and 12 GPa shock pressures levels which were more than three to six times as high as the Hugoniot Elastic Limit (HEL) of the same alumina and the shock recovered alumina fragments were characterized by X-ray diffraction (XRD), nanoindentation, scanning electron microscopy (SEM), field emission scanning electron microscopy (FE-SEM) and transmission electron microscopy (TEM). Based on these results a new qualitative damage model was developed to explain the deformation mechanisms of shock loaded alumina.

1. Introduction
HEL data on Alumina is available only for fine grain sizes [1-2] and rarely for coarse grain size [3]. This is what forms the basic scope and objective of the present work.

2. Experimental Materials and Methods
Symmetric shock experiments were conducted on a 10 μm grain size coarse alumina ceramic (density 3.98 gm.cc⁻¹) with a gas gun to identify its Hugoniot Elastic Limit (HEL) which was found from experimental measurement to be about ~2 GPa [3] which was a bit too much on the lower side than expected for alumina [1,2] presumably due to the large grain size, residual porosity and / or error due to the uncertainties of measurement. To understand the damage initiation and their subsequent growth mechanisms in coarse grain alumina subjected to shock impact at levels much above the HEL, additional asymmetric shock recovery experiments with a stainless steel flyer plate were deliberately conducted at 6.5 and 12 GPa with the same gas gun on the same alumina [4]. Detailed characterization of the shock recovered alumina fragments were done by XRD, nanoindentation, SEM, FE-SEM and TEM. Further experimental details are given elsewhere [3-6].

3. Results and Discussions
XRD of as received alumina (ARA) and shocked alumina (SA) from 6.5 and 12 GPa shock recovery experiments showed evidences of peak shift (figure 1a,b) to lower angles confirming the presence of a strained lattice [3,4]. The typical nanoindentents in ARA (figure 1c) and the corresponding load (P) – depth (h) plots for both ARA and SA samples (figure 1d) showed elastic-plastic deformation behaviour. SEM images of the SA samples from 6.5 GPa shock recovery experiments confirmed the characteristic presence of intergranular macrocracking (figure 2a) and intragranular microcleavages (figure 2b) with grain localized micro / nano-scale deformations, while the corresponding FE-SEM images show presence of both in-plane and out of plane shear deformation band of about 50-100nm
width (figure 2c,d) in single grains suggesting thereby the important role played by shear induced deformation and fracture processes and that the deformation and fracture processes indeed originate at the sub-microstructural or nanostructural length scale regime of the microstructure [5,6].

Figure 1. XRD (a,b), microstructure (c) and P-h plots (d) of ARA and SA.

Figure 2. SEM (a,b) and FESEM (c,d) images of SA at 6.5 GPa peak stress.

The SEM image of SA samples from the 12 GPa shock recovery experiments showed extensive grain boundary crack formation (figure 2a) and grain localized microcleavages (figure 2b) while the FE-SEM images showed high spatial density of 40-60 nm thick shear deformation bands in adjacent grains (figure 2c) as well as 20-40 nm thick shear deformation bands in mutually perpendicular directions (figure 2d) in single grains. Further FE SEM images of the SA 12 GPa sample showed microwinging crack formation (figure 4a) and parallel array of grain localized shear deformation bands oriented at about 70° angle to the horizontal direction (figure 4b). The presence of such high shear stress component led to TEM images which showed extensive presence of dislocations impeded at grain boundary (figure 4c, 6.5 GPa) and dislocation entanglement within single grains (figure 4d, 6.5 GPa). Thus, the shock recovered alumina samples form 6.5 and 12 GPa shock experiments showed a multitude of microdamages. These included micro-cleavages, grain-boundary microcracks, microwinging crack formation, and extensive shear induced deformations. In addition fractures localized at
grains, grain boundaries and triple grain junctions, grain localized dislocations and their pile up impeded at grain boundaries were observed (figures 2-4). The shock at higher pressure created more extensive surface and sub-surface damages. These microdamages lead to the presence of a stronger indentation size effect (ISE) in the nanoindentation experiments in the SA (6.5 and 12 GPa) samples compared to that of the ARA sample (figure 5) wherein the solid lines show that the presence of ISE in all the data could be nicely described by the Nix and Gao model [7].

Numerous efforts have been made earlier to model the high strain rate shock induced impact failure of brittle ceramics but no particular importance was given to coarse grain alumina ceramics [7-13]. These models either considered strength of the intact and the comminuted material [7], or assumed [8] an existing distribution of micro-cracks that grow according to dynamic fracture mechanics. Others [9] considered nucleation and growth of penny-shaped microcracks in multiple-planes and a balance between time dependent fracture and rate-dependent plasticity that allowed yield surfaces to vary with strain rate of the shock pulse delivered [10]. Recent attempts [1] tried to establish the role of grain localized plasticity in determining HEL. Efforts were made to depict [11] that surface of a crack slide to form wing cracks under multiaxial compression when the resolved applied shear stress exceeds frictional stress due to normal forces on the crack surfaces. For the present alumina ceramics the critical resolved shear stress for shear fault formation was estimated [3] to be 2.4-4 GPa which was much lower than the applied shock pressure of 6.5 GPa. These estimates matched also with those reported by others [2] for alumina. Therefore, shear stress induced deformation was quite possible for the present alumina ceramics. Further, it has been argued [3] that the dislocation pile up length of the present alumina sample would be on the higher side as it had a comparatively larger grain size e.g. ~10 μm, and consequently, a lower magnitude of critical shear stress would be necessary to nucleate a microcrack (figure 3a) at the head of the dislocation pileup (figure 4c) from a favourably oriented slip plane. Recent micromechanical finite element modeling [12] indeed have showed that the onset of plastic deformation in alumina results from grain boundary shear (that must first occur in order for wing cracks to form) that creates a tensile stress acting on two neighbouring suitably oriented grain boundaries (figure 4b) leading to mode I fracture thus forming a “micro-wing crack” (figure 4a). On continued loading, these tensile microcracks began to join hands with each other eventually to form cracked microstructural scale slabs in the case with no lateral confinement, i.e. similar to the case of the present experimental conditions. The molecular dynamic simulation work [13] on dynamic failure of glass also supports this picture. However, from the results of the shock recovery experiments (figs.
1-4) we can possibly not guarantee whether the cracks and / or micro scale defects formed exactly in compression during loading or under tension during unloading. Ceramics being characteristically brittle most of the defects supposedly generate due to the compressive as well as shear stress during loading at such high impact stress [1, 2, 8-9] and the additional sub-major defects might grow and / or generate under tension during unloading [10-13].

Based on the experimental data and evidences from SEM, FE-SEM and TEM observations of the present work a new, simplistic, qualitative damage model (figure 6) was developed to explain the deformation mechanisms of coarse grain alumina ceramics shock loaded to stress levels much above the HEL. As indicated in the model (figure 6), apart from the characteristic brittle fracture; inelastic damage growth, coalescence and fragmentation process in shocked alumina can happen by shear fracture initiation in a favourably oriented single grain at a single plane (ii,i’), or at multiple planes (ii,ii’), and / or by twist fracture initiation in a favourably oriented grain at a single plane (iii,iii’), or at multiple planes (iv,iv’) and the process repeats itself within a few μs at multiple grains (v). It is suggested that when these cracks grew, coalesced and propagated very fast the fragmentation of shocked alumina happened. However, future efforts shall be directed to verify this picture by computer simulation.

![Figure 5. ISE in ARA and SA samples.](image1.png)

![Figure 6. Model of shock damage in alumina.](image2.png)

4. Summary
Based on the experimental results a new qualitative damage model was developed to explain the deformation mechanisms of shock loaded coarse grain alumina.

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