Damage Evolution Mechanisms in Plate Impact of Alumina

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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 GPa shock pressures levels which was more than three times as high as the Hugoniot Elastic Limit (HEL) of the same alumina and the shock recovered alumina fragments were characterized by 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
Numerous damage models have been developed earlier to describe the high strain rate shock induced impact failure of mainly fine grained brittle ceramics [1-9] but significant attention had not yet been given to coarse grain alumina ceramics [10]. The Bourne model [1,2] emphasized the role of grain localized plasticity in determining HEL of fine grained alumina while the Johnson-Holmquist model considered strength of the intact and the comminuted ceramics [3]. The Rajendran model assumed [4] that a distribution of micro-cracks exist in a fine ceramic microstructure and their growth is dictated by the principles of dynamic fracture mechanics. The model proposed by Espinosa et al. [5] considered nucleation and growth of penny-shaped microcracks in multiple-planes of fine grained ceramics. The Grady model proposes that a fine competitive balance between time dependent fracture and rate-dependent plasticity linked processes dominates the shock induced local yielding in brittle ceramics as a function of strain rate [6]. The Horii and Neemat-Nasser model [7] proposed that surface of a crack present in a fine ceramic microstructure can 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. Micromechanical finite element modeling [8] have proved that the onset of plastic deformation in alumina results from grain boundary shear. The molecular dynamic simulation of the dynamic failure of glass also [9] supports this picture. Therefore, the objective of the present work was to propose a new damage evolution mechanism in plate impact induced high strain rate deformation and fracture of a dense, coarse grain e.g. 10 µm alumina ceramic.

2. Experimental Materials and Methods
A pressureless sintered alumina of density higher than 99.9% and 10 µm grain size was used in the present work [10]. At first the symmetric shock experiments were conducted on the alumina ceramic with a two stage gas gun to identify its Hugoniot Elastic Limit (HEL). The HEL was measured to be about 2 GPa commensurate with its large grain size [10]. To understand the damage initiation and their subsequent growth mechanisms in coarse grain alumina subjected to shock impact at levels more than three times the HEL, additional asymmetric shock recovery experiments were deliberately conducted at 6.5 GPa with a stainless steel flyer plate with the same gas gun on the similar 10 µm grain size alumina [11-13] processed in an identical manner to result in a similar microstructure. Detailed characterization of the shock recovered alumina...
fragments were done by FE-SEM and TEM. Further experimental details are given elsewhere [10-13].

3. Results and Discussions

The experimental results are shown in figures 1-3 and the model in figures 4a-d. Based on the experimental data and evidences from the FE-SEM and TEM observations of the present work (figures 1-3) the new damage model (figure 4) was developed. The FE-SEM images of the shocked alumina (SA) samples confirmed the characteristic presence of intergranular microcracking, grain boundary cracks (figure 1a) and grain localized micro / nano-scale deformations (figure 1b) in suitably oriented grains, the presence of both in-plane and out of plane shear deformation band of about 50-100nm width (figure 1c) in single grains and a characteristic presence of intraganular shear induced microcleavages where the individual shear fractured plates of a single grain (figure 1d) were only 40-50 nm thick. This observations suggest (i) the important role played by shear induced deformation and fracture processes (ii) the deformation and fracture processes indeed originate at the sub-microstructural or nanostructural length scale regime of the microstructure [12,13]. The FE-SEM image of Fig. 2a showed further the most important role played by grain orientation where a micro-wing crack had formed only in between the large and suitably oriented grains at the centre of the photomicrograph while the other grains were relatively unaffected. As indicated in the model (Figure 4a), 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 when its boundary with the adjoining grain shears out [7,8] to form a micro-wing crack (figures 4a and 2a). The formation of the micro-wing crack creates a tensile stress [7,8] acting on two neighboring suitably oriented grain boundaries leading to mode I fracture (figure 4b). On continued loading, these tensile microcracks began to join hands with each other to form eventually a cracked microstructural scale slab in the case with no lateral confinement which was similar to the case of the present experimental conditions. In addition, as a result of the propagation of the shock wave through the present alumina sample; a significant amount of shear stress becomes operative [3-13] both in-plane and out of plane (figure 1b,c) in the shock loaded microstructure. In-fact the FE-SEM image of figure 2b showed micro-shear deformation bands only on suitably oriented grain facets and grain faces at the triple grain junction while other grain faces were less affected. For the present alumina ceramics the critical resolved shear stress was estimated [10] to be 2.4-4 GPa which was much lower than the applied shock pressure of 6.5 GPa. These estimates (2.4-4 GPa) matched also with those reported by others [2] for alumina. Therefore, shear stress induced deformation and / or micro-fracture was quite possible to happen in the present alumina ceramics. Due to such high shear stress the single and / or multiple deformation bands can form in a suitably oriented grain and / or grain assembly in the microstructure (figures 1b,c and 4b). Also, in FE-SEM images of figures 2c and d very severe intragranular microcleavage had occurred in a suitably oriented single large grain while the grains around this large grain did not suffer so much of microcleavages. Such microcleavage can only occur due to micro-shear (figure 4c) and / or micro-twist fracture (figure 4d). The micro-shear induced failure (SF) can occur due to in-plane shear stresses either at a single plane ($SF_1$) or at multiple planes ($SF_{m}$) of a suitably oriented grain [5] and / or grain assembly as indicated in figure 4c. Similarly, the micro-twist induced failure (TF) can occur due to out-of-plane shear stresses either at a single plane ($TF_1$) or at multiple planes ($TF_{m}$) of a suitably oriented grain and / or grain assembly as indicated in figure 4d. Both of these processes can also lead to grain boundary micro-crack formation as indicated in figures 4c,d and was indeed experimentally observed (figures 1a,b). These two processes can work independent of each other or may be simultaneously operative depending on the actual energetics of the process which physically
depends on the locally active magnitude of the shock wave stress component and the relative orientation of the grain and/or grain assembly with respect to the direction of propagation of the shock wave and its own immediate microstructural surroundings.

The TEM images showed dislocation entanglement at triple point along with deformation band in adjacent grains (figure 3a), grain boundary micro-crack formation, and a region of very fine (5-50 nm) agglomeration of adhered debris smeared on the fractured grain (figure 3b), (c) micro-cracks and dislocations around highly plastically deformed grain (figure 3c), dislocations and deformation band formation in a single grain (figure 3d); thus confirming a major role of high shear stresses. Further, it has been argued [10] 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 micro-crack (figure 3b) at the tip of the dislocation pileup from a favourably oriented slip plane (figures 3c,d). Such a micro-crack can then quite easily act as a failure initiation point. As the
shock wave actually propagates in three dimensions, these micro-cracks grow very fast within a few μs at the nano and / or micro-structural length scale and link up by repetitive process through a multitude of grains with each other to coalesce at the microstructural length scale first. Eventually when many such events happen within a very small (few μs) time scale, the fracture propagates to cover the macrostructural length scale. The quick repetition of such a generic process is proposed to lead to the fragmentation of the shock loaded coarse grained high density alumina as observed the present work.

4. Summary
The shock recovered alumina fragments from a plate impact test at 6.5 GPa with a two stage gas gun were characterized by FE-SEM and TEM. In addition to the characteristic brittle compressive fracture, the shock fragments showed characteristic damage evolution features of grain localized micro / nano-scale deformations, micro-cleavages, grain boundary micro-cracks, micro-wing crack formation, extensive shear induced deformations and fractures localized at grains and grain boundaries as well as grain localized dislocations and damaged grain boundary smeared with nanoscale debris. Based on these results a new damage model based mainly on micro-shear and micro-twist fracture initiation, coalescence and propagation was developed to explain the failure mechanisms of shock loaded dense, coarse grain alumina in plate impact experiments.

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