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Dynamic Compressive Fracture of Ceramic Polymer Layered Composites

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Abstract

Dynamic compressive fracture evaluation is an essential characterization technique for advanced monolithic structural ceramics like alumina. Thus, for high strain rate induced damage tolerant applications, it is needed to take care of the characteristically brittle microstructure of the alumina ceramics. Hence, a smarter design concept has been involved based on the idea that cracks can either be arrested or deflected if a weak interface or interphase can be introduced. Thus, ceramic polymer layered composites (CPLC) were fabricated from high (e.g., 97%) density alumina disks pressureless sintered from sub-micron (d_{50}-0.6□m) alumina powder. The dynamic fragmentation of the CPLC samples at a reasonably high e.g., 900.s^{-1} strain rate has been studied with the real time, high-speed, in-situ video images, obtained during their failure in SHPB tests. A new failure mechanism has been proposed based on these data and FESEM evidences of grain boundary microcrack, inter/intra-granular shear bands and micro-fracture/cleavage formation.

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Keywords: Alumina, Split Hopkinson Pressure Bar, Deformation, Failure Strength.

1. Introduction

Ceramic materials are extensively used in dynamic load bearing applications, however, a proper set of ceramic material selection and their design is needed to mitigate the dynamic impact. Layered alumina are expected to find more applications in the dynamic load bearing fields provided their compressive failure mechanisms are better understood and the structural design can be improved accordingly. However, even for monolithic alumina, the reasons of compressive microfracture and their role in the global failure process during the shock wave propagation at high strain rate in dynamic stress field are far from well understood [1-2].

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Failure of high purity fine grain alumina under compression was associated with higher critical resolved shear stress to operate on a slip plane [3], presence of basal twins [4], occurrence of tensile stress field around damage induced defects, strain rate sensitivity and grain boundary microcracking due to dislocation pile-ups [5-7]. Recently attempt has been made to develop more reliable monolithic alumina ceramics with enhanced fracture strength and with improved fracture toughness involving smarter energy release mechanism [8]. Weak interfaces or interphases can deflect or arrest cracks on laminar composites by creating gradients in elastic modulus [9]. However, failure conditions are controlled the interfacial toughness and strength of the individual layers [10]. Though metal-ceramic structures were advantageous over conventional layered materials [11], but, the bi-layer patterns delivered weak multi-hit strength [12]. The basic predicament of having higher strength with hard ceramic as frontal with metal backup is impedance mismatch which may induce tensile failure of the ceramic material [13]. To overcome this problem, functionally graded materials have been thought of as alternative because layer-by-layer the impedances are changed and as a result the tensile stress can be reduced [14-15].

Nevertheless, the interest for understanding about the mechanisms involved in the deformation process at high strain rates has fascinated researchers to study this phenomenon exhaustively to improve the overall performance under dynamic stress exposure conditions. Also newer applications in the emerging fields have unravelled various methodologies to understand the deformation mechanisms by involving latest analytical, computational and characterization tools. Split Hopkinson Pressure Bar (SHPB) is a commonly used tool to generate dynamic compressive stress-strain responses of materials. Dynamic fractures become easy to analyse if diagnostic instruments like high speed imaging systems are included during the loading of specimen. Though high-speed photography exhibits how fracture fronts propagate, but that the photographs need to be interpreted with care. The present SHPB experiments using copper pulse shaping technique with a high-speed synchronized camera were conducted on the specimen to assuage primarily the thirst of our understanding about the live failure process of the specimen at high strain rate. Thus, the present experiments were planned as a preliminary investigation in this context for deeper understanding of the operative physical mechanisms involved in the deformation process of ceramic layered structure. Split Hopkinson Pressure Bar (SHPB) technique has been adopted along with synchronised high speed camera for capturing live failure process to get further insight into the details of damage evaluation during shock wave propagation in layered ceramics. To elucidate the deformation process Field Emission Scanning Electron Microscopy (FESEM) were performed to characterize the damage evaluation and fracture micromechanisms that happened during the damage initiation and propagation in alumina.

2. Materials and Methods

The alumina samples were pressureless sintered from sub-micron size (d_{50}-0.6□m) alumina powder. The diameter (d) and thickness (l) of the sintered alumina specimens used for the split hopkinson pressure bar (SHPB) tests were kept in the range of 6.00 ± 0.05 and 3.00 ± 0.03 mm respectively. Two such specimens are joined together by using commercial adhesive to get a layered specimen. The size of the specimen has been selected mainly based on the capacity and requirement of our test system [16].

SHPB apparatus can be used to perform tests on layered specimens to get data recorded from strain gauges on the bars in the conventional manner [1]. High speed real time video images were captured to understand the details of the failure process in the high strain rate SHPB experiments. Before going for the actual experiment, bar-to-bar test with copper pulse shaper was performed (Fig. 1) to check out whether the apparatus was properly calibrated, aligned and reasonably friction free. The total deformation mechanisms of the layered specimen were captured within 16 frames. The circuitry of the high speed camera was synchronised with the incidence of the projectile in a manner such the calculated delay in triggering the picture-shots would enable the camera to capture the entire deformation processes limited to 16 frames (Fig. 2).

3. Results and Discussions

The important assumption that has been made in the Hopkinson bar theory is the deformation of the specimen that occurs under uniaxial stress once the stress equilibrium is achieved within the specimen after the application of the impulsive force. This assumption is most unlikely to be satisfied when two or more materials of different acoustic impedance are clubbed together. In the present experiment, the overall compliance of the system is not affected due to displacement of the sample as the transfer of load has been arranged in series in power train.

For materials having high value of modulus and elastic limit, this displacement offers a wide stress interval and in the case of having low value of modulus and/or elastic limit a reasonably lesser stress interval can be achieved. Therefore, stress interval is another important factor to this dynamics. Hence, the material properties i.e., elastic modulus, yield stress, density are intricately involved in the wave propagation of the multi-layer materials making the system more complex in comparison to a monolithic one. In fact, severe stress inhomogeneities at the interfaces have developed, and consequently significant stress gradients should be formed at and within the boundaries the interfacial layer.

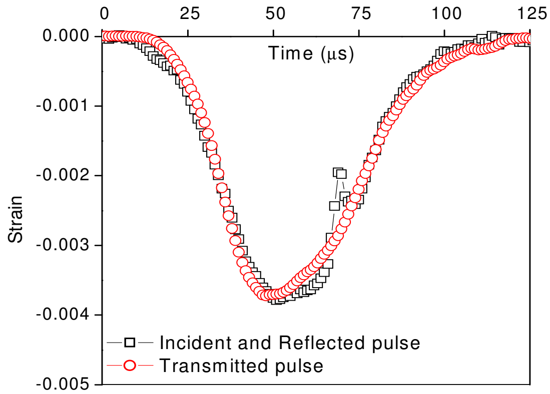

Figure 1. Bar-to-bar test indicated that the incident pulse got overlapped on the transmitted pulse to establish the condition of equilibrium of the apparatus satisfactory for performing the experiment.

The equilibrium condition of the present SHPB experiment was examined by performing bar-to-bar test with copper pulse shaper and showed in Fig. 1. One can find in Fig. 1 that the curves representing incident and reflected pulse, and that of the transmitted pulse have overlapped with each other. The present condition has established that the apparatus was properly aligned, frictionless and fit for performing the experiment.

The collage of the video images of failure phenomena of the layered alumina sample captured in 16 frames using high-speed camera during the dynamic loading process is shown in Fig. 2. Both the tungsten carbide platen disks were visible in the photographs. Pictures corresponding to frame numbers 1 to 4, Fig. 2, were almost similar. Prominently after 15 μs, the photo-frames 4 and 5 in Fig. 3 exhibited the splashing of the grease from the surfaces of the incident and reflected platens. The crushing of the specimen just began as indicated by arrows in the picture corresponding to 5th frame at the instant of 25 μs from the surfaces attached to the platens, Fig. 3. The deformation of the specimen initiated globally from the surface attached to the *reflected platen* (indicated by white arrow, frame 6, Fig. 3). The specimen was loaded up to its failure strength and became flattened in frame 8 and almost got completely crushed by the time of frame 10 as drawn by dotted line in frame 8 and 10 of Fig. 3. In other words the specimen was loaded till the peak strength of ~3.2 GPa at the instant of ~50 μs, Fig. 3 and 4. Afterwards it began to lose its load carrying capacity progressively and totally lost its strength as revealed in frame 16, noted at the instant of 80 μs, Fig. 3.

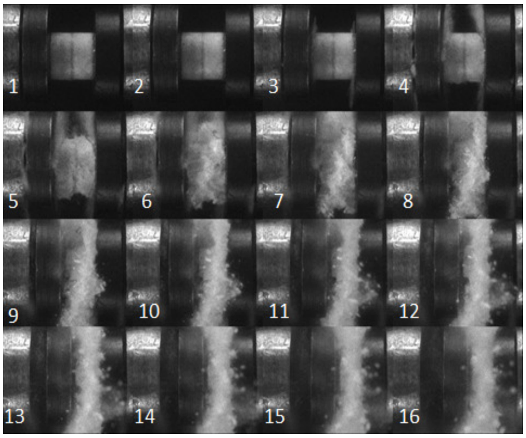

Figure 2. High speed videography shows the failure of layered alumina sample during dynamic loading in 16 frames in the present experiment.

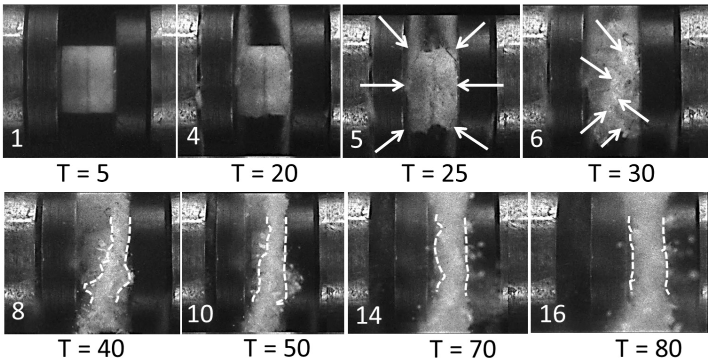

Figure 3. Selected photo-frames of high-speed videography attached in the present SHPB experiment showing the real-time deformation process of the sample during dynamic loading with the corresponding time (T) in μs.

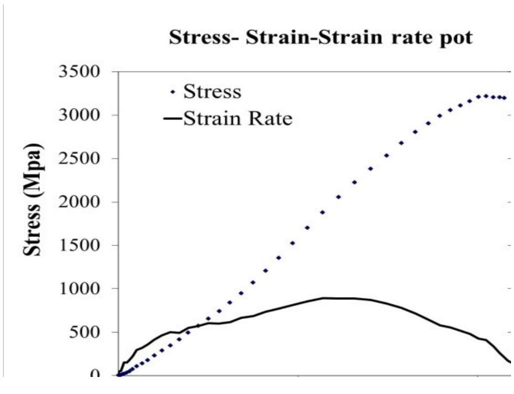

Figure 4: Stress and Strain Rate of layered alumina composites as a function of strain

FESEM was used to study the deformation mechanisms that followed during the deformation process. The photomicrographs revealed many observations of the fracture mechanisms of the specimen subjected to uniaxial state of stress equivalent to those of under uniaxial state of strain condition.

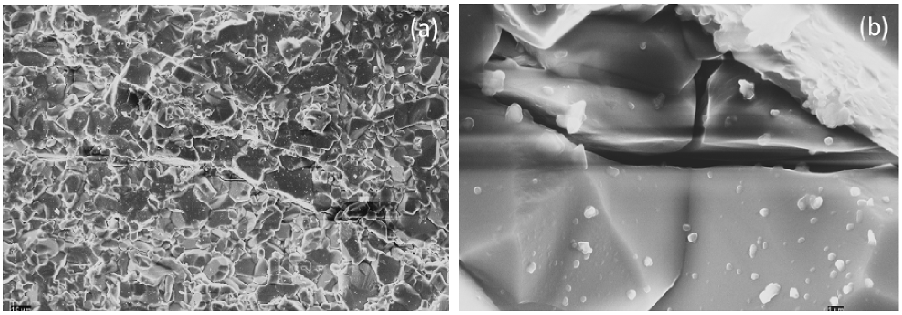

Figure 5. (a) Typical fracture surface of shocked recovered alumina depicted the propagation of crack damaging the grains and grain boundaries and (b) subsequent perpendicular transmission through the weak links.

High strain rate impact initiated high rate of loadings. Such loadings kicked off large number of cracks which subsequently relieved the stress in a short span of time affecting the grain or grain boundaries whichever had at that instant of time required the least amount of energy [Fig. 5(a) and (b)].

Fig. 6 indicated that the sample underwent complex failure process that occurred at high strain rate condition in a given grain or grains in multiple planes as oriented to the direction of the compressive pulse propagation. The formation of shear plane with plastic deformation and grain localised stepped microfracture [Fig. 6(a) and (b)] strongly suggested that the above deformation mechanism occurred only when both in plane and out of plane shear deformation modes were active during the failure process. Thus, the layered specimen had steep stress gradients individually and therefore each specimen was susceptible to get fractured separately, as was also experimentally observed (Fig. 3).

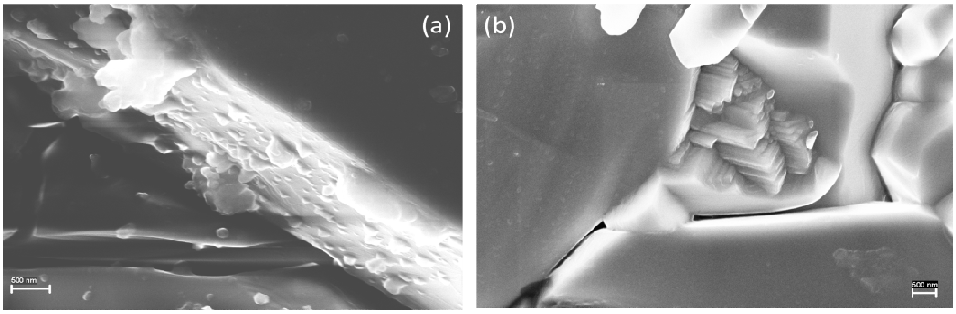

Figure 6. Formation of shear plane with significant plastic deformations (a) and grain localised stepped micro-fracture (b) observed.

4. Summary and Conclusions

The objective of the present experiment was to use a layered alumina sample under SHPB experiment to develop a better understanding about the reasons of compressive microfracture and their role to the global failure process. High-speed photography was employed to study the real-time pictures of the failure process. The dynamic compressive strength of the layered alumina/polymer composite was about 3.2 GPa at a strain rate of 900-1000s^{-1}. The survival period of the layered specimen was found to be ~50 μs which is significantly stretched by reducing the severity of stress concentration in the layered parts due to the presence of a very thin polymer layer. This survival period was higher than that (e.g., 40μs) typically found for the monolithic alumina exposed to similar high strain rate compressive stress application. Extensive characterisation of the shocked recovered alumina samples revealed widespread shear deformation confined at suitably oriented grains and grain boundaries. The shock waves were active at a single and/or multiple planes which either individually or jointly gave the last call in the failure of a suitably oriented grain or assemblage of grains. Brittle layers are very prone to fracture due to formation of sharp stress-strain gradients. By ascertaining the relative contribution of yield stress, modulus, density and wave properties it may be possible to design a better and forthcoming layered composites to optimise fracture characteristics.

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