Dilatation of AD995 Alumina Impacted by Two Consecutive Stress Pulses during a SHPB Experiment

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Summary

The dynamic compressive responses of AD995 alumina have been determined as a function of loading rates, damage levels, and damage-induced dilatation. To determine the dynamic properties under loading conditions simulating those encountered in ceramic armors subjected to impact, a novel dynamic compressive experimental technique modified from a split Hopkinson pressure bar (SHPB) was employed to load the ceramic specimen by two consecutive stress pulses. The first pulse determines the dynamic response of the intact ceramic material and then crushes the specimen. The second pulse determines the dynamic compressive constitutive behavior of the ceramic rubble that is still interlocked. The separation of these two pulses is varied to study the damage-induced dilatation effects on the compressive response of the ceramic specimen. The results show that the compressive strengths of damaged ceramics are insensitive to the separation between the two pulses once the damage level exceeds a critical value.

Introduction

For ceramics in armor systems, the lack of precise dynamic material constitutive models remains to be a significant design challenge [1,2]. The local tensile stresses around the grain boundaries, defects, and other inhomogeneties, exceed the tensile strength of the ceramic under even moderate compressive loading from a long-rod projectile striking a ceramic armor [3], which causes the ceramic material to be eventually pulverized. Many cracks will propagate/interact simultaneously, forming a comminuted zone around and ahead the tip of the penetrator [4-7]. The fine fragments in ceramic target ahead of the penetrator flows radially around the penetrator's nose and is then ejected backwards along the shank that is thus erode until it vanishes or the ceramic is perforated [8]. It is therefore desired to determine the dynamic compressive response of the damaged or pulverized ceramic, which still remains interlocked rather than becoming loose powder at high strain rates.

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The behavior of the damaged and interlocked ceramic as a function of strain rate and damage has been initially investigated [9,10].

In this paper, we present the dynamic compressive responses of intact and damaged but interlocked AD995 alumina. The results were obtained using a new dynamic experimental technique modified from a SHPB that sends two consecutive stress pulses to a ceramic specimen. The first pulse determines the dynamic compressive response of the intact ceramic and then crush the specimen. The second pulse determines the dynamic compressive stress-strain behavior of the crushed but still interlocked ceramic. The separation of two pulses is varied through pulse shaping to study the damage-induced dilatation effects on the compressive response of the damaged ceramic specimen before it disintegrates.

Experiments

An effective approach to achieve the dynamic compressive response of the damaged or pulverized ceramic is to employ two consecutive loading pulses, achieved through the employment of two strikers in a series, in a single dynamic SHPB experiment [9,10]. The first pulse crushes the intact specimen into rubble after characterizing the intact material. The extent of the impact-induced damage can be controlled through the control of the profile of the first pulse. Just after the unloading of the first pulse, or even before the first pulse is unloaded completely, while the damaged ceramic still remains interlocked, a second pulse loads the damaged specimen. A pulse shaper between the two strikers controls the separation between these two loading pulses. The separation time is varied in this study to study the damage-induced dilatation effects on the compressive response of the ceramic. Besides the desired double loading pulses in a single experiment, a second modification to a SHPB in this study is the employment of a universal joint along the loading axis to ensure the proper alignment of the brittle specimen.

The two strikers, launched from the gas gun barrel of a SHPB setup as schematically shown in Fig. 1, were separated by pulse shapers. The first striker, a steel bar, impacted the incident bar through a pulse shaper, a C11000 annealed copper attached to the impact end of the incident bar, and created the first stress pulse. Then a second striker bar, either an aluminum bar or a steel bar depending on the desired strain rate in the specimen, is employed to generate the second loading pulse. A combination of the length of the first and second striker, the striking velocity, and the geometry of two pulse shapers controls the desired strain rate as well as the damage level in the specimen [11,12]. The second pulse shaper separates the second loading pulse from the first one. Variations in the material and geometry of this pulse shaper provides various separation time, as well as ensures the damaged samples to deform under dynamic stress equilibrium at constant strain rates. The dimensions of pulse shapers at various strain rates were selected through trial experiments guided by analytical models [11].

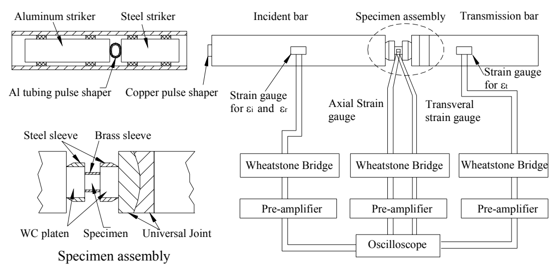

Fig. 1. A schematic illustration of the dynamic experimental setup for double loading.

To minimize the stress concentrations in the brittle specimen due to grip rigidity and alignment [10,13-15], a pair of laterally confined tungsten carbide platens were placed between the specimen and the bars, preventing the specimen from indenting into the bars. A simplified spherical universal joint was placed between the tungsten carbide platen and the transmission bar to achieve self-adjusting alignment [13].

To prevent the specimen from shattering completely, the cylindrical ceramic specimen was slightly confined by a thin-walled metal sleeve on the lateral surface, following an established heated-up procedure [15]. To determine the dilatation history in the specimen, two strain gauges, along and perpendicular to the loading axial direction, were mounted on the metal sleeve's surface to directly measure the axial and transverse strains. The volume strain of the specimen was calculated through the summation of the measured strains with transverse strain count twice. Since the yield strain of the sleeve material is less than the axial failure strain of the ceramic, if the first pulse is completely unloaded, the measured strain associated with the second pulse may not be accurate due to the residual strain in the sleeve material at the end of unloading by the first pulse. The contribution to the transmitted signal by the thin sleeve was subtracted from the total transmitted signal in the stress calculation. The contribution from all the contacting surfaces was also subtracted from the reflected signal [9,10].

The dimensions of the cylindrical specimen used in this research were 6.35 mm in diameter and 6.35 mm in length. The materials were Coors Tek AD995 alumina with density 3900 kg/m^3, Young's modulus 370 GPa, Poisson's ratio 0.22, and quasi-static compressive strength 2.8 GPa. The sleeve was made of a brass with an inner diameter of 6.345 mm and an outer diameter 6.99 mm, with the same length as the specimens. A typical set of the incident and transmitted pulses recorded by a digital oscilloscope may be found in previous papers by the authors [9,10]. After using the 1-wave, 2-wave method to check the dynamic equilibrium, the data is reduced to obtain the dynamic stress-strain histories in the specimens.

The relative density of the damaged ceramic was considered as an important parameter that affects the mechanical response of the specimen. To examine the density effects, or dilation effects, four dynamic experiments were conducted. To damage the intact ceramic at the same level and achieve the same strain rates in the crushed specimen, the first and second pulses are the same, respectively, in the four experiments. However, the separation time between the two loading pulses is varied.

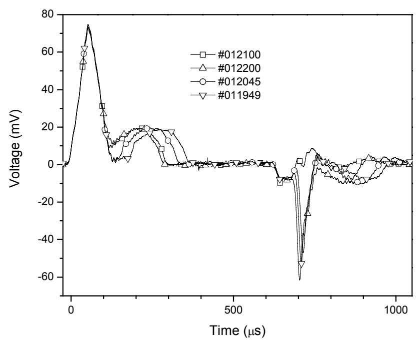

Fig. 2. Incident bar signals of SHPB to determine the dilatation effects on AD995

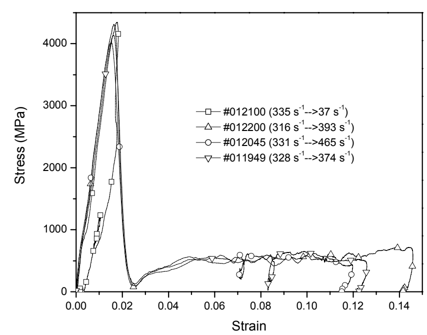

Fig. 3. Dynamic stress-strain curves of intact and damaged AD995 alumina.

Figure 2 shows the incident-bar pulses for the four experiments. Figure 3 shows the corresponding dynamic compressive stress-strain curves. During the deformation of the ceramic specimen, the confining pressure from the brass sleeve on the ceramic can initially be neglected when the specimen is under elastic deformation or is damaged only slightly. After substantial damage, the sleeve confines the interlocked rubble at an estimated pressure of 26 MPa through the plastic deformation of the metal sleeve.

As shown in Fig. 3, a specimen initially behaves as a typical brittle material with a linear stress-strain curve. It deviates from linear response at a stress of ~3.5 GPa and then fails catastrophically near the peak stress of ~4.3 GPa. After failure, the stress sharply decreases to near zero. One of the four specimens is not completely crushed, which is marked “012100” in Fig. 3 and is considered as the result of the variation among specimens. As the axial strains in the crushed samples increase under the compression from the second load pulse, the lateral confinement from the thin metal sleeve maintained an axial “flow” stress of about 500 MPa. The uncrushed sample withstands the peak of the second pulse that corresponds a stress of 1200 MPa in the specimen. Even though the second pulse was controlled to arrive during unloading, at the end of unloading, and after unloading of the first pulse, no clear variation was observed in the "flow stress" of the crushed specimen except for the less-damaged one. This indicates that the remaining strength of the damaged ceramic is not sensitive to the arrival time of the second pulse. However, there seems to be a critical damage level below which the ceramic remains nearly elastic.

Figure 4 shows volume dilatation history measured by strain gages mounted on the thin metal sleeves. Figure 5 shows the dilatation history plotted against axial strain. The results indicate that, except for the uncrushed specimen, specimen volume starts to increase drastically at an axial strain level of just below 1%, which corresponds approximately to where stress-strain behavior deviates from linear.

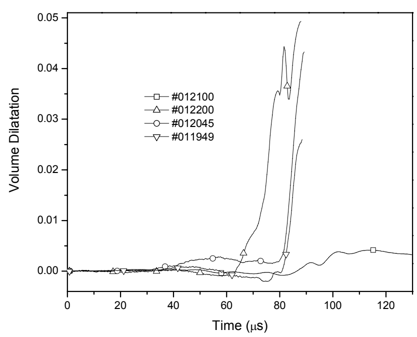

Fig. 4. Dynamic dilatation history of AD995.

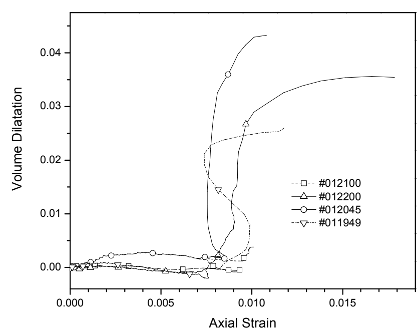

Fig. 5. Dynamic dilatation-axial strain curve of AD995

Conclusions

The dynamic compressive mechanical responses of an intact and damaged AD995 alumina were determined with a novel dynamic experimental technique modified from a SHPB which loads the ceramic specimen by two successive stress pulses. Experimental results show that the damaged ceramic is not sensitive to the separation of the two pulses because damage occurs even before the unloading of the first pulse.

Acknowledgments

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