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Impact of Alumina Rods - A Computational and Experimental Study

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Résumé : Des expériences d'impact combinant la mesure de vitesse par interférométrie ont été réalisées pour déterminer le comportement de barreaux d'alumine Coors-AD995. Des matériaux d'impédance variable ont été utilisés pour impacter à la fois le barreau nu et des barreaux revêtus de manchons. Les résultats de calculs avec le code CTH démontrent les caractéristiques uniques de cette nouvelle méthode : ① une impulsion de contrainte dépendante du temps généré au cours de l'impact permet la transition progressive d'un état de déformation uniaxiale vers un état de contrainte uniaxiale, et ② une vitesse de chargement intermédiaire est obtenue entre la technique des barres de Hopkinson et la technique d'impact de plaque classique.

Abstract: Gas gun experiments combined with velocity interferometric techniques have been used to experimentally determine the loading behavior of a Coors-AD995 alumina rod 19 mm in diameter by either 74 mm or 151 mm in length. Graded-density materials were used to impact both bare and sleeved alumina rods, while the velocity interferometer was used to monitor the axial-velocity of the free end of the rods. Results of these experiments and CTH calculations will demonstrate a unique feature of this novel test methodology: (1) a time-dependent stress pulse generated during impact allows for a smooth and efficient transition from the initial uniaxial strain loading to a uniaxial stress state as the stress pulse propagates through the rod, and (2) the intermediate loading rates obtained in this configuration lie between those available from split Hopkinson bar and shock-loading techniques and are not achieved easily by either one of these techniques.

1. INTRODUCTION

There is a need for accurate ceramic material models to facilitate computational and engineering analyses involving ceramic materials under dynamic loading. Well-controlled impact techniques and high-resolution diagnostics [1] are generally used to determine the baseline material property data, often under uniaxial strain conditions. This is the first step necessary to determine the equation-of-state and constitutive material properties such as the yield strength or fracture strength of materials under transient loading. Such a data base forms the foundation for material models that have been developed for engineering analysis in computer codes.

Validation and the continued development of ceramic material models appropriate under multiaxial loading conditions will, however, requires the existence of a comprehensive material property data base. It is the purpose of this paper to report new measurements on alumina under a broader range of dynamic loading conditions. Gas gun experiments, combined with velocity interferometric techniques, have been used to experimentally determine the loading behavior of a Coors-AD995 alumina rod ~ 19 mm in diameter by 74 mm and 151 mm in length. Graded-density materials [2,3] have been used to impact both bare and sleeved alumina rods, while the velocity interferometer was used to monitor the axial-velocity of the free end of the rods. Results of these experiments and CTH [4] calculations will demonstrate unique features of this novel test methodology: (1) a time-dependent stress pulse generated during impact allows a smooth and efficient transition from the initial uniaxial strain loading to a uniaxial stress state as the stress pulse propagates through the rod, and (2) intermediate loading rates obtained in this configuration lie in a region which is not achieved easily by either split Hopkinson bar or shock-loading techniques.

2. MATERIAL

The aluminum oxide used in this study is generally referred to as Coors AD995. Its composition consists of 99.5% alumina and the rest aluminosilicate glass. The density of the material used in this investigation was 3.89 g/cm³; the average longitudinal and shear wave speed was determined to be 10.59 km/s and 6.24 km/s, respectively. This yields an estimate of 7.71 km/s, 9.80 km/s, and 0.234 for the bulk wave velocity, bar wave velocity, and Poisson's ratio, respectively. Specifically, this is the same batch of material used in previous studies on alumina [5-7].

Figure 1. Calculated radial (xx) stress and axial (yy) stress configuration along the axis of the bare rod 6 μ s after impact by a single density material.

Figure 2. Free-surface (axial) velocity history vs time at Lagrangian points 0.0, 0.2, 0.4, 0.6 0.8 cm from the axis of the rod. Note the radial velocity disparity that results from single density impact.

3. COMPUTATIONAL ANALYSIS

CTH calculations were used to optimize the experimental design used in these series. A key objective of the design calculations was to prevent the fracture of alumina during the initial loading phase. An elastic plastic model was assumed for all materials. Extremely large values of fracture stress (> 10 GPa) were used for each material to allow a meaningful design calculation—which is to prevent significant tension states from being produced during the initial loading phase. When a single-density material impacts the rod, then the loading is immediately followed by release waves originating at the circumferential free-surface of the rod-impactor interface. This will attenuate the stress pulse as it propagates into the rod. The rate of stress attenuation depends on the location relative to the circumferential free-surface. Points along the axis of the rod are attenuated the latest. The interaction of these radially emanating release waves generate lateral tension states in the rod. Even though the mean pressure of the rod indicates compression, radial tension stress components will cause brittle failure of the ceramics if the fracture strength of the material is exceeded.

3.1 Single Density Impact

One of the objectives of this study was to impact load the alumina rod to a stress level near its reported Hugoniot elastic limit of about 6.7 GPa [5,8]. CTH-calculation results of 4340 steel impacting an alumina rod 74 mm long at a velocity of 0.35 km/s are indicated in Figure 1. Impact results in a peak stress of ~ 7 GPa at the impact interface. At 6 μ s after impact the calculations indicate that the axial peak stress decays to about 4 GPa, while the radial stress component along the axis of the rods suggests tension states approaching 2 GPa during loading. The spall strength of the material when shocked below its elastic limit is about 0.5 GPa [5,8]. Alumina is strong in compression, but weak under tension - a property that is characteristic of many brittle materials. Axial velocity history at the free surface and at Lagrangian points located at 0.0, 0.2, 0.4, 0.6, and 0.8 cm along the radius and from the center axis of the rod show considerable velocity disparity. This is shown in Figure 2. This suggests that the stress propagation has not transitioned into a uniaxial stress state after a propagation distance of ~ 74 mm. This is further evidenced in Figure 1, which indicates a radial stress component of about 0.9 GPa during loading.

3.2 Graded-Density Impact

To minimize the radial stress tension components, a graded-density impactor was used to impact the alumina rod. This method has been used successfully, for example, to prevent fragmentation of flier-plates when launched to hypervelocities of 16 km/s [2,3]. A graded-density impact also results in a peak stress of ~ 7 GPa at the impact interface, but the loading occurs over a finite time duration of $\sim 3 \mu$ s. The release waves emanating at the circumferential free surface of the rods will also release the material over a longer time duration when compared to a single-density impact. The competing effects between release and loading results in (1) lowering the magnitude of the radial tension to ~ 0.5 GPa the fracture strength of alumina, as alumina is loaded to about 4 GPa (see Figure 3), and (2) the loading to a peak stress of about 4 GPa is gradual compared to the oscillatory and erratic loading (due to release effects) structure seen in Figure 1 for a single-density impact. (A higher tension state of about 0.8 GPa at late times is observed towards the impact interface.) Results of the axial free-surface velocity history in Figure 4 at Lagrangian points located at 0.0, 0.2, 0.4, 0.6, and 0.8 cm from the center axis of the rod show a negligible velocity disparity when compared to the results of a single density impact shown in Figure 2. This indicates that for this configuration the stress propagation does transition to uniaxial stress after traversing only 74 mm. This is also evidenced in Figure 3, which now indicates a radial stress component of about 0.4 GPa during loading.

Figure 3. Calculated radial (xx) stress and axial (yy) stress configuration along the axis of the bare rod 6 μ s after impact by a graded-density material.

Figure 4. Calculated free-surface (axial) velocity history vs time at a radius of 0.0, 0.2, 0.4, 0.6, 0.8 cm from the axis of the rod. Note the radial velocity disparity is minimized, when a graded density impactor is used.

3.3 Graded Density Impact on a Sleeved Rod

To further reduce the radial stress tension components, a graded-density impactor was used to impact a sleeved-alumina rod. 4340 steel was used as a sleeve because its shock impedance is very similar to alumina. The rod diameter is effectively doubled. In this calculation a slide treatment was invoked i.e., alumina was allowed to slide along the alumina rod and the steel interface. A graded-density impact will result in a peak stress of ~ 7 GPa at the impact interface over a finite time duration of $\sim 3 \mu$ s. The release waves emanating at the circumferential free surface of the sleeve will arrive at a later time to release the stress states in alumina compared to the results of the unsleeved graded-density impact. This (1) prevents any interaction of radial release waves from generating tension states in the material during loading to a higher peak stress of about 5 GPa even as late as 6 μ s after impact (see Figure 5), and (2) the loading to a peak stress of about 5 GPa is "smoother" compared to the loading structure seen in Figure 3 for a graded-density impact. (A higher tension state of about 0.8 GPa generated at late times is observed towards the impact interface.) The axial free-surface velocity history (Figure 6) at Lagrangian points located radially at 0.0, 0.2, 0.4, 0.6, and 0.8 cm from the center axis of the rod show a negligible velocity variation when compared to a single density impact. This strongly suggests that the wave propagation has transitioned to a uniaxial stress motion after traversing 74 mm (even though the effective length to diameter ratio is only 2). This is also evidenced in Figure 5 which indicates radial stress components of ~ 0.4 GPa. This is considerably lower when compared to the results of a single density impact shown in Figure 1.

4. EXPERIMENTAL TECHNIQUE

These experiments were performed on a 64 mm diameter smooth-bore, single-stage compressed gas gun which is capable of achieving a maximum velocity of about 1.6 km/s. Three electrically shorting pins were used to measure the velocity of the projectile at impact. Four similar pins were mounted flush to the impact plane and used to monitor the planarity of impact. Projectile velocity could be measured with an accuracy of about 0.5% and the deviation from planarity of impact was a few milliradians. The graded-density

Figure 5. Calculated radial (xx) stress and axial (yy) stress configuration along the axis of the sleeved rod 6 μ s after impact by a graded density material.

Figure 6. Calculated free-surface (axial) velocity history vs time of a sleeved-alumina rod at a radius of 0.0, 0.2, 0.4, 0.6, 0.8 cm from the axis of the rod. Note the radial velocity dispersion is also minimized as in Figure 4.

Figure 7. Experimental configuration of a layered/impactor and a ceramic-rod target assembly.

impactor assembly is fabricated by bonding a series of thin plates in order of increasing shock impedance from the impact surface. The series of layered materials used in these studies were TPX-plastic, aluminum, titanium, and 4340 steel. The thickness of each layer is controlled to tailor the time-dependent input stress pulse into the alumina rod. This is shown in Figure 7, and the exact dimensions of each material assembly is given in Table 1. This layered material assembly is used as a facing on an aluminum projectile and is accelerated on a gas gun to velocities of about 320 m/s, providing a time-dependent loading to ~ 6.5 GPa. The experimental target assemblies consisted of either a bare or a sleeved alumina rod ~ 19 mm in diameter. The length of the rods in this study were nominally 74 mm or 151 mm. When used, 4340 steel was chosen for the close fitting sleeve material to provide a good shock impedance to the alumina sample. The outer diameter of the sleeve was nominally 39 mm. Mechanical coupling between the rod and the sleeved was achieved by filling the narrow annulus (0.025mm) with epoxy. When unsleeved, a polyurethane foam was used to decouple the rod from the aluminum target fixture. A 0.055 mm thick tungsten reflector glued onto the free surface of the rod was used to obtain the axial particle velocity measurements using the velocity interferometer, VISAR [9], having a time resolution of about 1 ns. These measurements are shown in Figure 8 for the series of experiments summarized in Table 1.

Table 1: Summary of impact experiments on AD995 alumina rods

Test No.	Rod Diameter/Length (mm)/(mm)	Impactor Materials	Impactor Thickness (mm)	Impactor Velocity (km/s)	Sleeved
FW1	19.164/73.67	Steel	10.59	0.318	no
FW2	19.169/73.67	Steel/Ti/Al/TPX	19.04/1.097/1.199/1.034	0.321	yes
FW3	19.162/150.32	Steel/Ti/Al/TPX	19.05/1.123/1.204/1.024	0.321	yes
FW4	19.172/151.38	Steel/Ti/Al/TPX	19.04/1.102/1.204/1.041	0.322	yes
FW5	19.159/73.668	Steel/Ti/Al/TPX	19.06/1.107/1.204/1.024	0.300	no
FW6	19.192/152.41	Steel/Ti/Al/TPX	19.08/0.998/0.998/0.975	0.366	no

5. RESULTS

5.1 Single Density Impact vs. Graded Density Impact - Unsleeved Experiments

The experimental result for a single density impact (FW1) is indicated in Figure 8. The wave profile reveals a distinct two-wave structure, i.e., the arrival of an initial elastic compression wave (2.1GPa) at a wave speed of 10.6 km/s followed by the arrival of a second compression wave traversing at a bar wave speed of 9.8 km/s. This results in loading the alumina to a final stress of 3.4 GPa. However, when a graded density impactor is used to impact the rod (FW5), the leading edge of the initial compression wave loads the material to only 0.2 GPa and travels at a speed of 10.6 km/s. Subsequent wave arrives at a bar wave speed of 9.8 km/s and loads the material to a final stress of 3.5 GPa at a strain-rate of ~ 4 x 10³ /s. Even

Figure 8. Free surface particle velocity profiles representing the axial velocity measurements for all experiments in Table 1.

though the impact velocity of the experiment FW5 is approximately 6% lower than the single density impact experiment FW1, the peak particle velocity attained in the graded-density impact experiment is slightly higher. In the graded density impact experiment FW6, the rod is ~ 150 mm long, and the impact velocity is 0.366 km/s, approximately 10% higher than the single density impact experiment. The elastic precompression wave is attenuated to 0.1 GPa, compared to the 0.2 GPa in experiment FW5; the subsequent compression wave traversing at the bar wave velocity loads the material up to a state of 4.2 GPa at a strain rate of 4.5×10^3 /s, and eventually relaxing to a stress state of ~ 3.6 GPa. The first compression state σ_1 is calculated using $\sigma_1 = (\rho_0 c_l \Delta u_{fs})/2$, where ρ_0 is the initial density, c_l the elastic wave speed, and Δu_{fs} the incremental free surface velocity measurement associated with the longitudinal elastic wave. The axial compression state σ_a and the loading strain rates ϵ associated with the bar wave is calculated using $\sigma_a = (\rho_0 c_b \Delta u_{fs})/2$ and $\epsilon = \Delta u_{fs}/(2c_b t)$, where c_b is the bar wave velocity, and Δu_{fs} the corresponding free-surface velocity measurement, and t the time duration for loading.

5.2 Graded Density Impact - Sleeved Experiments

Experimental results for sleeved experiments FW2 (74 mm rod), FW3 & FW4 (151 mm rod) are also shown in Figure 8. Graded density impactors were used in these experiments. In each case, the initial elastic compression wave traversing at 10.6 km/s loads the material up to stress states of 0.2 GPa and 0.1 GPa, respectively, for the short and the long rods. For the short rod and the long rod experiment, the subsequent compression wave traversing at a bar wave speed compresses the material to a final stress of 5.1 GPa and 4.6 GPa, respectively. The corresponding loading rates are approximately 5×10^3 /s and 4.5×10^3 /s, respectively. The results of these experiments are shown plotted as the failure stress vs. strain-rate [10] in Figure 9.

6. CONCLUSIONS

Previous studies on impact of alumina rods [11-12] have concentrated upon using a single density impactor to evaluate the uniaxial compressive behavior of the ceramics. However, as mentioned above, due to the low spall strength of alumina, the radial stress components suggests fracture in the material [12] even though the mean stress of the material indicates compression. This is not desirable if the interest is to investigate the deformation mechanisms of ceramics under dynamic compression. The technique proposed

Figure 9. Dynamic failure properties of selected brittle solids under quasistatic and dynamic compressive loading.

herein i.e., using graded-density impactors to study the uniaxial compressive behavior of the rods circumvents this problem by reducing the magnitude of tension generated in alumina. As indicated earlier a sleeved rod totally prevents the formation of radial tension during the loading process.

It is not surprising that the single-density impact experiment yields a failure stress of 3.4 GPa, the graded-density impact experiments fails at 4.2 GPa, and the sleeved experiments fails at 5.1 GPa. The material that is damaged the most fails at a lower stress. These results are consistent with the hypothesis that for brittle materials the onset of failure depends heavily on the loading rate. Shock experiments yield higher estimates of strength mainly because rate-dependent kinetics prevent the nucleation and growth of flaws and defects in materials during rapid loading. The loading times in these experiments are of the order of a few microseconds. As indicated in Figure 9, this is typical for a variety of materials including geological materials [10] that are brittle. It would be useful to perform similar experiments on other brittle materials, including geological materials.

Calculational results indicate that the ratio of the lateral stress to the axial stress is ~ 0.23 for the single-density impact of the alumina rod, and ~ 0.1 and ~ 0.08 for the graded-density impact of the unsleeved and sleeved rod, respectively. This apparently indicates that the degree of confinement is least for the sleeved rod. It is consistent with the earlier inference that the stress propagation in the rods transitions to a uniaxial stress motion when it is loaded at finite rates. Therefore, the experimental measurements of a higher failure stress (5.1 GPa) for the sleeved rod when compared to the lowest value (3.4 GPa) are not due to the sleeved-confinement of the rod, but are more related to strain-rate sensitivities, as indicated in Figure 9. If the rod were rigidly confined, then one should measure an upper dynamic limit of 6.7 GPa which is the estimate for the Hugoniot elastic limit for this material.

The most significant result of this study is that the use of a graded-density impactor allows an efficient transition to the uniaxial stress configuration even though the ratio of the length to diameter of the rods is only around 4 for 74 mm rods when unsleeved, and effectively 2 when it is sleeved. This is obviously not the case for a single density impact, as indicated in Figure 2. Besides, a finite rate of loading allows a method by which strain-rate effects of the material can be determined. The current experiments address strain-rate effects in alumina at strain rates of $\sim 5 \times 10^3$ /s. The strength of alumina is estimated to be ~ 5 GPa. The strain-rate loading can be increased by decreasing the thickness of the graded density layers. A factor of four decrease in thickness should load the material at a strain rate of 2×10^4 /s. The technique, therefore, will permit accessibility to intermediate loading rates which are difficult to achieve either using traditional split Hopkinson bar or shock loading techniques. Furthermore, the stress amplitude of the wave propagating at the elastic longitudinal wave speed can be further reduced in these experiments by using a lower impedance material such as foam as the first layer in the series of graded density materials. As indicated in this study, the use of plastic as compared to steel (FW1) reduces the amplitude by over an order of magnitude from 2 GPa to ~ 0.2 GPa.

A closer examination between CTH calculations and experiments does, however, suggest some discrepancies. Calculationally, the peak particle velocity estimates are ~ 0.18 km/s for the single density impact configuration to ~ 0.20 km/s for the graded density impact on the sleeved or the unsleeved rod configurations. The corresponding estimates experimentally are 0.17 km/s for a single density impact, ~ 0.20 km/s for a graded-density impact on a bare rod, and 0.27 km/s for a graded-density impact on a sleeved rod. Calculationally, a significant relaxation is observed after loading in each case. Experimentally, the axial velocity measurements indicate a slight decay to a constant equilibrium value for the duration of the recording time. An exact agreement is not to be expected, because an extremely simple elastic-plastic model was used to design these experiments. As this study indicates, the material behavior is quite complex. It is anticipated that these experiments will form a data base to stimulate the development of multi-dimensional constitutive models needed for brittle materials.

In this study CTH-simulations were used primarily to look at trends in material loading behavior which has led to the design of these experiments. It appears that loading rates of a few times 10^4 /s can be achieved by optimizing the design of the graded density layered materials, the diameter of the bar, and the impact velocity. Concepts are currently being pursued to achieve yet higher loading rates of 10^5 /s. One approach under consideration is to use the graded-density materials as an impactor to perform isentropic loading experiments up to its Hugoniot elastic limit. These experiments will, however, characterize the material behavior under uniaxial strain loading.

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