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Intermediate Strain-Rate LoadingExperiments - Techniques and Applications*

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Gas guns and velocity interferometric techniques have been used to determine the loading behavior of AD995 alumina rods 19 mm in diameter by 75 mm and 150 mm long, respectively. 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 demonstrate that (1) a time-dependent stress pulse generated during impact allows an 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 split Hopkinson bar and shock-loading techniques.

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, require 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

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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 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.

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/cm^3; 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].

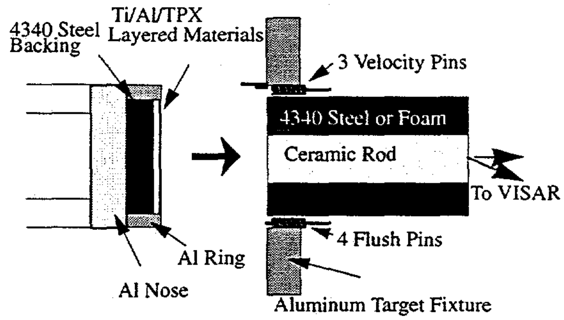

Figure 1. Experimental configuration of a layered/impactor and a ceramic-rod target assembly.

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 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. 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 lengths 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. 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 (6), having a time resolution of ~ 1 ns. These measurements are shown in Figure 2 for the 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

UNSLEEVED EXPERIMENTS

The experimental result for a single density impact (FW1) is indicated in Figure 2. 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 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 traversing at 10.6 km/s loads the material to only 0.2 GPa. A 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 ~ 4×10^3 /s.

Even 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, ~ 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 4.2 GPa at a strain rate of 4.5×10^3 /s, eventually relaxing to a stress state of ~ 3.6 GPa. The first compression state σ_l is calculated using $\sigma_l = (\rho_o c_l \delta u_{fs})/2$, where ρ_o is the initial density, c_l the elastic wave speed, and δu_{fs} the incremental free surface velocity measurement associated with the lon-

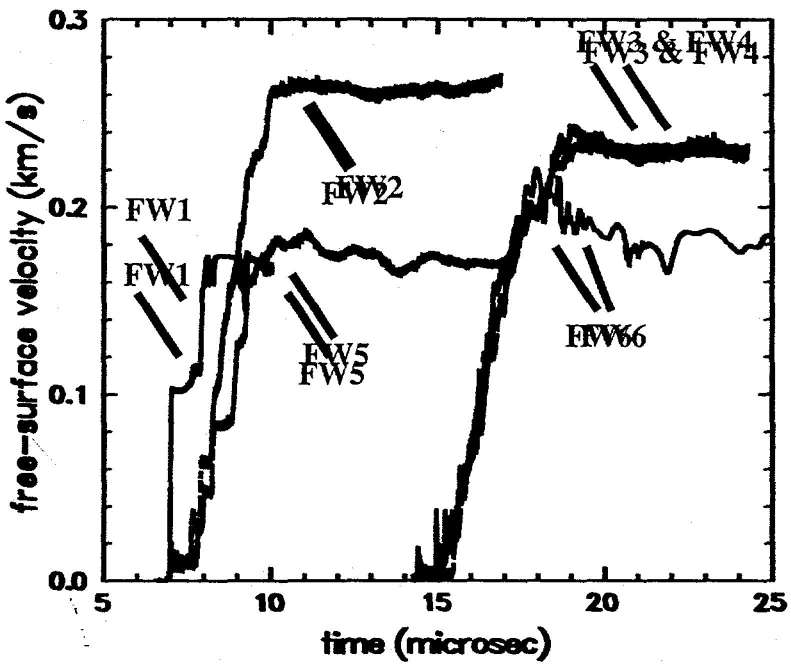

Figure 2. Free surface profiles representing the axial velocity measurements for all experiments in Table 1.

gitudinal elastic wave. The axial compression state σ_a and the loading strain rates ε associated with the bar wave are calculated using $\sigma_a = (\rho_o c_b \Delta u_{fs})/2$ and $\varepsilon = \Delta u_{fs}/(2c_b t)$, where c_b is the bar wave velocity, and Δu_{fs} the corresponding free-surface velocity measurement, and t the time duration for loading.

SLEEVED EXPERIMENTS

Experimental results for sleeved experiments FW2 (74 mm rod), FW3 & FW4 (151 mm rod) are also shown in Figure 2. Graded density impactors were used in these experiments. 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. 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 x 10^3 /s and 4.5 x 10^3 /s, respectively. The results of these experiments are shown plotted as the failure stress *vs.* strain-rate (7) in Figure 3.

CONCLUSIONS

Previous studies on impact of alumina rods (8-9) have concentrated upon using a single density impactor to evaluate the uniaxial compressive behavior of the ceramics. However, due to the low spall strength of alumina (3,10), the radial stress components will fracture the material (9,11) during the loading phase even though the mean stress of the material indicates compression. The technique proposed 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. 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 (shown in Figure 3.) 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.

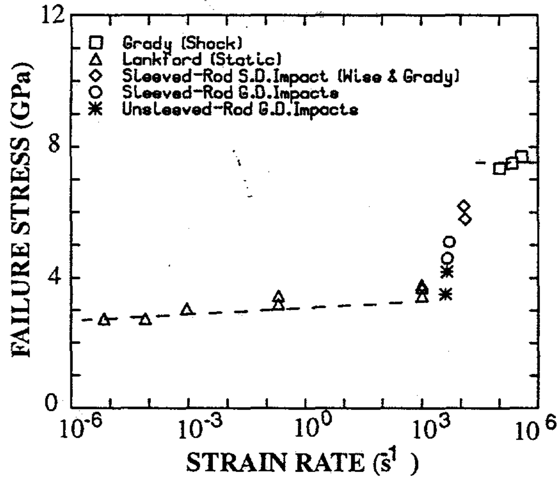

Figure 3. Failure stress of AD995 alumina as a function of loading rate. Quasi-static and shock loading results are also shown.

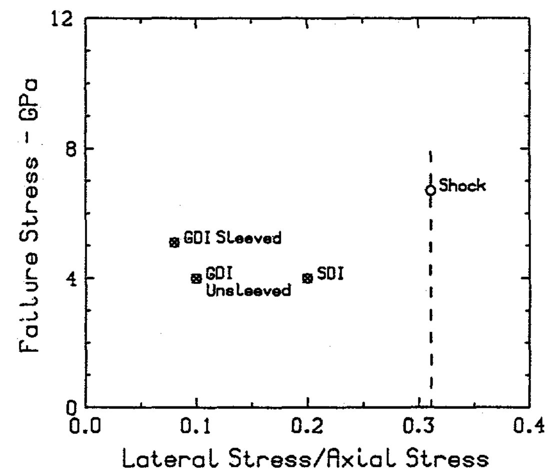

Figure 4. Variation of calculated failure stress as a function of confinement i.e., the ratio of lateral stress to axial stress

CTH-calculational results (11) 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, and is also depicted in Figure 5. 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 3. If the rod were rigidly confined, then one should measure an upper dynamic limit of 6.7 GPa which is the Hugoniot elastic limit (3,10).

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. Besides, a finite rate of loading allows a method by which strain-rate effects of the material can be determined. This is obviously not the case for a single density impact (11), as evidenced by a two-wave structure in Figure 2.

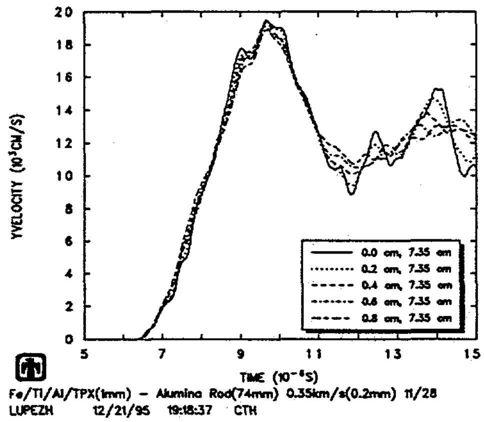

Figure 5. Calculated free-surface axial velocity history at a ra-

The current experiments address strain-rate effects in alumina at strain rates of ~ 5 x 10^3 /s. The strength of alumina is estimated to be ~ 5.1 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 x 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 (FW5) as compared to steel (FW1) reduces the amplitude of the elastic wave by over an order of magnitude from 2 to ~ 0.2 GPa

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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