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DYNAMIC, MULTIAXIAL IMPACT RESPONSE OF
CONFINED AND UNCONFINED CERAMIC RODS

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A new configuration for impact testing was implemented which yielded time-resolved measurements of the dynamic response of materials undergoing multiaxial strain. With this method, one end of an initially stationary rod (*i.e.*, right circular cylinder) of test material was subjected to planar impact with a flat-faced projectile. The test rod was either free (unconfined) or mounted within a close-fitting sleeve which provided lateral confinement. Velocity interferometer diagnostics monitored the axial (longitudinal) velocity of the rod free end, and the transverse (radial) velocity for one or more points on the periphery of the rod or confinement sleeve. Analysis of the resultant velocity records allowed assessment of material properties, such as wave speeds and compressive yield strength, without the requirement of intact recovery of the rod. Data were obtained for alumina (Coors AD-99.5) rods in a series of tests involving variations in confinement and peak impact stress.

INTRODUCTION

The development of material models and computer codes which successfully simulate dynamic impact events is dependent on the existence of an appropriate materials-property database. Continued work on *multidimensional* constitutive models and wavecodes requires concurrent acquisition of data characterizing material response in multiaxial loading environments which produce stress-strain conditions that are not achievable under planar shock (uniaxial strain).

For the traditional Taylor test [1], a free-flying ductile rod impacts a "rigid" anvil, and post-test observation of the position of the boundary between the unstrained and plastically-deformed regions of the rod yields an estimate for the dynamic, compressive yield strength of the rod material under uniaxial stress. This estimate relies on simplifying assumptions regarding the motion of the elastic/plastic boundary from the impact end of the rod to its final, measured (post-test) position. Analyses of such tests

ignore the effects of radial inertia and require intact recovery of the rod.

With the present test method, the *anvil* was launched, and it struck an initially stationary, flat-ended rod of test material. This rod was either free or mounted within a sleeve which afforded lateral confinement. Velocity interferometer (VISAR) diagnostics [2] detected the axial (longitudinal) surface velocity for the free end of the rod, and the transverse (radial) velocity for one or more points on the periphery of the target rod or confinement sleeve. Unlike the Taylor test, analyses of the velocity records did not rely on simplifying assumptions regarding rod deformation, and yielded velocity histories which provided wave speed and compressive yield strength information without the requirement for intact rod recovery. These features made the new technique particularly attractive for studies of brittle ceramics which are inherently unsuitable for evaluation with the Taylor method since they invariably fracture for impact stresses in excess of the yield strength.

* This work performed at Sandia National Laboratories supported by the U.S. DOE under contract #DE-AC04-76DP00789.

CONF-930670 4
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Figure 1. Impact test arrangement.

EXPERIMENTAL CONFIGURATION

The geometry for impact studies on confined and unconfined ceramic rods is illustrated in Figure 1. For all five experiments (designated 3, 3A, 4, 5, 6) discussed in this paper, ceramic rods were fabricated from Coors AD-99.5 alumina (polycrystalline Al_2O_3). Each rod was machined to a final diameter, D , of 10.06 mm, and to a final length, L , of 80.00 mm ($L/D = 8$).

For experiments involving no lateral confinement (shots 3, 3A, 5), the ceramic rod was mounted directly within a low-density (360 kg/m^3) polyurethane foam collar which, in turn, was held by an aluminum support ring. For the confined tests (shots 4, 6), the ceramic rod was first installed in a close-fitting, metallic (tantalum, Ta) sleeve which had an outer diameter of 20.00 mm and length of 80.00 mm, then this sleeve was mounted within a foam collar whose density was 290 kg/m^3 . Tantalum was selected as a sleeve material because of its ductility and high shock impedance.

The foam effectively decoupled the rod or sleeve from the high stresses produced in the support ring by projectile impact. To delay the arrival of foam debris at VISAR measurement locations, a 3.4-mm thick PMMA (polymethylmethacrylate) shield plate (not shown in Figure 1) covered the rear surface of the foam collar. Mechanical coupling between the

ceramic rod and Ta sleeve was achieved by filling the narrow (0.012-0.025 mm thick) annulus between them with thin-set epoxy.

Dynamic loading of the rod or rod/sleeve assembly was produced by a flat-faced projectile launched from a single-stage propellant gun. The monolithic impactor, or anvil, was fabricated from 6061-T6 aluminum, and featured (1) a forward flat-plate section that was nearly full bore diameter (89 mm) and nominally 12.7-mm thick, and (2) a trailing rod section that was 20.00-mm diameter and 122-mm long. This rod section was incorporated as a means of maximizing the duration of high stress levels at the impact end of the target rod.

Coaxial shorting pins mounted around the support-ring periphery were struck by the plate section of the impactor and generated signals which permitted determination of impact velocity and tilt. The selected impact velocities of 1.1 and 2.1 mm/ μs , respectively, produced peak stresses in the ceramic rods of either 2 or 4 times the 6.16-GPa Hugoniot elastic limit (HEL) which has recently been measured for Coors AD-99.5 alumina [3].

MATERIAL PROPERTIES

Ultrasonic longitudinal, C_L , and shear, C_S , wave speeds, and reference density, ρ_0 , were determined for each alumina (AD-99.5) rod, Ta sleeve, and aluminum (6061-T6) impactor. The mean values of these measurements are listed in Table 1, along with calculated values for the bar wave velocity, C_B , and Poisson's ratio, ν .

Table 1: Elastic Properties.

Material	ρ_0 kg/m^3	C_L $\text{mm}/\mu\text{s}$	C_S $\text{mm}/\mu\text{s}$	C_B $\text{mm}/\mu\text{s}$	ν
AD-99.5	3892	10.591	6.244	9.808	0.2336
Ta	16607	4.131	2.068	3.377	0.3328
6061-T6 Al	2709	6.398	3.140	5.143	0.3414

EXPERIMENTAL RESULTS & DISCUSSION

Data are reported here for the five experiments noted above. Table 2 shows the parameters for each test. In all cases, VISAR #1 monitored the *axial* mo-

Table 2: Test Conditions.

Shot No.	Impact Velocity mm/ μ s	Tilt mrad	Sleeve Material
5	1.035	1.78	none
6	1.051	1.86	Ta
3	2.175	---	none
3A	2.182	7.38	none
4	2.140	0.83	Ta

tion of the rod free end which was 80 mm from the initial impact plane, while VISARs #2 and #3 monitored the *radial* motion of the rod or sleeve outer surface at stations which were, respectively, 30 and 50 mm from the initial impact plane. The velocity-perfringe sensitivity was 0.1394 mm/ μ s for VISAR #1, 0.1085 mm/ μ s for VISAR #2, and 0.07167 mm/ μ s for VISAR #3.

Free-Surface Velocity Measurements

Figure 2. Axial (VISAR 1) and radial (VISARs 2 & 3) velocity histories for shot 5.

Velocity records for experiments 5 and 6 are displayed, respectively, in Figures 2 and 3. In both experiments, axial velocity data were successfully recorded by VISAR #1 during a time interval extending at least 25 μ s after first detectable motion. Qualitatively, the axial-velocity records were characterized by the arrival of an initial elastic compression (propagating at a velocity close to the measured value of $C_L = 10.6$ mm/ μ s), followed by a second compressional wave (travelling at approximately the bar wave velocity, $C_B = 9.81$ mm/ μ s) that brought the surface velocity to its peak value. The axial velocity subsequently decayed slightly from this peak (about 10% and 20%, respectively, for tests 5 and 6), attaining an essentially constant equilibrium value that persisted for the duration of the recording time.

Shorter recording intervals were achieved for the radial-velocity data in tests 5 and 6: about 9-12 μ s for VISAR #2, and about 12-15 μ s for VISAR #3. For the unconfined rod (test 5), the radial-velocity records indicated similar amplitudes for the first peak, but divergent behavior thereafter with higher velocities being observed at the downstream point. For the confined rod (test 6), the radial histories showed mutually consistent structure and amplitudes with the downstream record (VISAR 3) indicating wave attenuation. Negative values of radial

Figure 3. Axial (VISAR 1) and radial (VISARs 2 & 3) velocity histories for shot 6.

Figure 4. Axial (VISAR 1) and radial (VISARs 2 & 3) velocity histories for shots 3 & 3A.

velocity for test 6 at times in the 9-15 μs interval were qualitatively and quantitatively consistent with pretest wavecode simulations done by Swegle [4] using ARTOO [5].

Referring to Figure 4 (tests 3 & 3A) and Figure 5 (test 4), axial and radial velocities were also obtained for tests at higher impact velocities; however, recording intervals were shorter than noted above due to earlier arrival of target debris at VISAR locations.

Despite a factor-of-two increase in impact velocity, the equilibrium axial velocity for test 3A was nearly identical to that for test 5 which also involved an unconfined rod. Similarly, considering the pair of tests on confined rods, the equilibrium velocity for test 4 exceeded that for test 6 by no more than 10%.

Yield-Strength Estimates

In these tests, the amplitude of the equilibrium axial velocity was primarily dependent upon the level of lateral confinement. The corresponding *in-situ* axial stress was estimated using these equilibrium velocities and the bar wave velocity of the alumina rod. On this basis, an *in-situ* axial stress of 3.15 GPa was obtained for shots 3A and 5 (no confinement), compared to 6.32 and 5.80 GPa, respectively, for tests 4 and 6 (Ta confinement). This increase in stress-wave amplitude with increased confinement

Figure 5. Axial (VISAR 1) and radial (VISARs 2 & 3) velocity histories for shot 4.

was consistent with expectations of an upper dynamic limit equal to the HEL of alumina (6.16 GPa) for the case of rigid confinement (*i.e.*, uniaxial strain). Pressure dependence of the yield strength may account for a wave amplitude in the unconfined rods (3.15 GPa) which was lower than the reported dynamic yield strength of 4.3 GPa for AD-99.5 [3].

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