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Shock-Wave Strength Properties of Boron Carbide and Silicon Carbide*

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Résumé: Afin d'évaluer les propriétés de solidité et d'équation dynamique de céramiques de carbure de silicone et de carbure de boron, nous avons effectué des mesures de vitesse interférométrique à résolution temporelle. Les caractéristiques de tendance Hugoniot, ainsi que les propriétés d'ondes de rendement après choc et échappement, indiquent des tendances manifestement différentes pour les deux carbures, en ce qui concerne leur force dynamique et le comportement du flux.

Abstract: Time-resolved velocity interferometry measurements have been made on boron carbide and silicon carbide ceramics to assess dynamic equation-of-state and strength properties of these materials. Hugoniot precursor characteristics, and post-yield shock and release wave properties, indicated markedly different dynamic strength and flow behavior for the two carbides.

1. INTRODUCTION

Certain of the intermetallic light weight compounds, in the form of polycrystalline ceramics, exhibit some of the highest strength properties measured on engineering materials. Limited plastic slip systems in these materials preclude plastic flow at lower stress levels, and dynamic strengths approach an appreciable fraction of the theoretical strength. Representative of these high-strength ceramics are the two carbides, B_4C and SiC , which exhibit comparable high Hugoniot elastic limits, ranging between 15-20 GPa. The post-yield dynamic strength characteristics of these ceramics exhibit markedly different behavior, however, and in the present study high-resolution time-resolved velocity interferometry diagnostics have been used to investigate these unique dynamic strength properties.

Thus, in this study, shock and release wave profiles in boron carbide and silicon carbide have been measured from peak stress states that are just in excess of the Hugoniot elastic limit to peak stresses approaching 60 GPa. Silicon carbide reveals an uncommonly high Hugoniot elastic limit (~15-16 GPa). Post-yield strength of silicon carbide, determined by comparison of Hugoniot uniaxial strain and calculated hydrodynamic response, reveals neutral or increasing strength with subsequent deformation beyond the initial dynamic yield. Boron carbide exhibits a somewhat higher Hugoniot elastic limit (~18-20 GPa). In contrast, however, subsequent deformation indicates a dramatic loss in strength supporting capability. Hugoniot and hydrodynamic response for boron carbide converge at stresses approaching about twice the Hugoniot elas-

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Fig. 1.- Shock and release wave profiles for silicon carbide and boron carbide ceramics measured with velocity interferometry diagnostics.

tic limit, suggesting little or no shear stress component at higher Hugoniot states. The contrasting dynamic strength characteristics of silicon carbide and boron carbide is further amplified in the release properties of these materials from the Hugoniot state. The release paths for silicon carbide indicate reverse yielding and continued strength characteristics of elastic-plastic material behavior. The unloading stress-volume paths for boron carbide closely parallel the calculated hydrodynamic behavior suggesting near fluid-like response with sustained loss of strength. Further features in the measured wave profiles indicate a heterogeneous deformation in boron carbide in contrast to homogeneous deformation in silicon carbide. Microscopic mechanisms are considered which may be responsible for the strikingly different shock and deformation properties of these two ceramics.

2. MATERIALS AND THE SHOCK-WAVE EXPERIMENT

Both silicon carbide and boron carbide ceramics were tested by shock-wave methods in the present study. The silicon carbide was supplied by Eagle Picher Industries. The density of this material is 3177 kg/m^3 . The longitudinal and shear elastic velocities are 12.02 and 7.67 km/s , respectively. The material has a porosity of approximately 1% and a nominal grain size of $7 \mu\text{m}$. Knoop hardness for this ceramic is 22.3 (¹). Shock wave data for this material has previously been reported (^{2,3}). The boron carbide investigated in the current work was provided by Dow Chemical Company. The density is 2506 kg/m^3 . Longitudinal and shear elastic velocities are 14.03 and 9.65 km/s , respectively. The nominal grain size is $3 \mu\text{m}$, porosity of order 1%, and Knoop hardness is 25.6 . Properties and microstructure differ slightly from another boron carbide provided by Eagle Picher Industries for which shock-wave data has previously been reported (²).

Planar shock and release wave experiments were performed on the monolithic ceramic samples with a single stage powder gun capable of 2.5 km/s maximum projectile velocity. Plates of the same ceramic, or a high density metal, were backed by low density polyurethane foam, mounted on the projectile, and caused to impact stationary target plates of the test ceramic. Target samples were backed by lithium fluoride windows approximately 25 mm in thickness and 50 mm in diameter. The transmitted particle velocity profiles produced by the impact-generated shock waves were measured with laser velocity interferometry (VISAR)

techniques ⁽⁴⁾. Details of the experimental method have been reported earlier ^(5,6). Measured shock and release wave profiles for silicon carbide and boron carbide are provided in Fig. 1. Experimental dimensions are noted in Table 1. In all tests the peak stress (ranging between about 25 and 50 GPa) exceeded the Hugoniot elastic limit of the ceramic. Striking differences in wave profile characteristics relating to the elastic precursor wave, the Hugoniot state, and the release structure are noted between the two ceramics. These differences are discussed further in the subsequent sections.

Table 1:
Experimental Conditions for Impact Tests.

Test Number	Foam ^a Density (kg/m ³)	Projectile Material	Projectile thickness (mm)	Target Material	Target Thickness (mm)	Impact Velocity (km/s)
CE-4	320	SiC	3.987	SiC	8.939	1.542
CE-5	640	SiC	3.995	SiC	8.940	2.100
CE-31	640	Tantalum	1.516	SiC	8.956	2.118
CE-17	320	B ₄ C	4.831	B ₄ C	10.322	1.633
CE-18	640	B ₄ C	4.815	B ₄ C	10.346	2.076
CE-26	640	Tantalum	1.514	B ₄ C	9.680	2.059

^a Polyurethane foam discs backing the projectile impact plate were approximately 6 mm in thickness.

3. ELASTIC PRECURSOR CHARACTERISTICS

Details of the elastic precursor waves for silicon carbide and boron carbide are shown in Fig. 2. The Hugoniot elastic limit is defined here as the break in slope following the steep rise of the initial wave arrival — a profile velocity of about 0.55 km/s for silicon carbide and about 0.7-0.8 km/s for boron carbide. Stress val-

Fig. 2.- Details of the elastic precursor wave profiles measured with VISAR diagnostics for silicon carbide and boron carbide.

Fig. 3.- Hugoniot shock velocity versus particle velocity data for silicon carbide and boron carbide.

ues for the Hugoniot elastic limit calculated by impedance matching methods are about 15-16 GPa for silicon carbide and 18-20 GPa for boron carbide. Post-yield characteristics of the precursor waves are dramatically different for the two materials, however. For silicon carbide the positive slope of the precursor wave reveals a subsequent hardening with further deformation to stresses in excess of 20 GPa. Whether pressure hardening or deformation hardening plays the more dominant role cannot be uniquely determined from the shock wave data. Nevertheless, significant resistance to dislocation plasticity or compressive shear fracture continues to persist in silicon carbide as dynamic shear deformation in the shock process proceeds.

Precursor waves for boron carbide, in contrast, indicate post-yield stress softening. Stress relaxation suggests a rate-sensitive deformation process, probably accompanied by precursor attenuation with propagation distance. The latter behavior has been confirmed by shock profile measurements on thinner samples (not presented here).

Finally it is worth noting in Fig. 2 the nearly a factor of two difference in time separation of the elastic wave and first indication of the following deformation shock wave between silicon carbide and boron carbide. This feature also reveals distinct differences in post-yield strength characteristics of the two ceramics.

4. HUGONIOT PROPERTIES

Hugoniot states achieved in the shock process are assessed by estimates of the elastic and deformation shock velocity from the profile data, and particle velocities from either the symmetry of the impact, the known Hugoniot curve of the impactor material, or the measured amplitudes from the wave profiles. The velocity of the elastic precursor was not measured in the present study. Instead the longitudinal elastic velocity was augmented by an estimate of the non-linearity of the material at the Hugoniot elastic limit $U_{hel} = C_l + Su_{hel}$, assuming a representative value of $S = 1$, to provide the elastic shock velocity U_{hel} . This estimated elastic shock velocity is about 4 to 5 percent larger than the elastic wave speed C_l . The deformation shock velocity is then referenced to the elastic shock wave velocity.

Fig. 4.- Data points are elastic and final shock Hugoniot states. The solid curve is the bulk pressure versus volume behavior from extrapolation of ultrasonic data. Dashed curves correspond to wavecode solutions to experimental VISAR profiles.

Shock velocity versus particle velocity data for silicon carbide and boron carbide are shown in Fig. 3. Both Hugoniot elastic limit and final Hugoniot states are identified. The dashed curve represents the bulk sound velocity, $C_o^2 = C_l^2 - 4C_s^2/3$, determined from ultrasonic data of Manghnani ⁽⁷⁾ to 2 GPa and extrapolated to higher pressure using the reported values for the zero pressure bulk moduli K_o and the pressure derivative K_o' . Hugoniot states for silicon carbide are in good agreement with the extrapolated bulk velocity and consistent with a material which retains a shear strength at the Hugoniot pressure comparable to the strength at the Hugoniot elastic limit. In contrast, shock velocities for boron carbide are markedly lower than bulk velocities suggesting significant reduction in the shear strength at the Hugoniot state. Open circles for boron carbide represent the new data (Fig. 1 and Table 1). Closed circles correspond to an earlier material which exhibited a slightly reduced Hugoniot elastic limit and somewhat higher deformation shock velocities ⁽²⁾.

Hugoniot states are plotted in stress versus specific volume space in Fig. 4. In addition to the data from Fig. 3, Hugoniot states for one experiment each for silicon carbide and boron carbide below the Hugoniot elastic limit reported previously ⁽⁸⁾ are shown. Also a recently measured Hugoniot point to nearly 58 GPa, using a two-stage light gas gun on a 3-mm thickness boron carbide sample, is included. Also shown in Fig. 4 are estimates of the bulk pressure versus volume response of both ceramics, again based on the ultrasonic data of Manghnani ⁽⁷⁾. A serious uncertainty in this construction arises from an unclear knowledge of the theoretical density of the ceramic materials. Ideally the theoretical density appropriate to this development should represent the zero porosity material accounting for any sintering impurities or differences in chemistry from the common formula unit. The reference densities used in Fig. 4 simply account for the nominal 1% porosities of these ceramics and may be uncertain by as much as a percent either way.

Comparisons of the Hugoniot data in Fig. 4 with the estimated bulk response generally support observations relating to shock velocity data in Fig. 3. For silicon carbide the measured Hugoniot states are offset substantially from the pressure-volume curve indicating retention of a substantial shear stress component. Boron carbide, on the other hand, upon exceeding the Hugoniot elastic limit, exhibits a dramatic increase in compressibility and achieves final Hugoniot states near the bulk pressure-volume curve. Post-yield

behavior for boron carbide would suggest nearly complete loss of shear strength. The fact that the 40 and 58 GPa Hugoniot points actually lie to the left of the estimated pressure-volume curve is of some concern. It may simply reflect the uncertainty in the initial theoretical density of this ceramic. It should be remembered, however, that the unique deformation processes initiated during shock compression could potentially lead to enhanced volumetric lattice compression (with corresponding change in lattice structure) which exceeds the calculated stable lattice compression based on the lower pressure ultrasonic data. Considering the unusual very open structure of the boron-carbide lattice (⁹), an anomalous volume compression under shock loading should not be ruled out.

Finally, complete shock and release wave profiles from several of the tests have been matched with one-dimensional wave code calculations by Kipp (^{2,3}) using adjustable parameter computational models. The three dashed curves for silicon carbide and two for boron carbide in Fig. 4 represent the stress-volume load and release curves corresponding to a satisfactory fit to these wave profiles. The nature of the curves for silicon carbide correspond remarkably well to a high-strength elastic-plastic material. Simulations of the boron carbide wave profiles, on the other hand, suggest loss of strength above the Hugoniot elastic limit and near-fluid-like behavior on stress release.

5. DISCUSSION

Markedly different dynamic compression and release behavior are noted in the shock compression characteristics of silicon-carbide and boron-carbide ceramics. The common methods of contrasting shock compression states with measured or estimated hydrostatic pressure-volume behavior suggests near-metal-like shock properties for silicon carbide in its strength-retention characteristics under a cycle of shock-wave compression and release. A similar comparison for boron carbide, however, indicates catastrophic loss of strength above the Hugoniot elastic limit with near-fluid behavior during subsequent deformation in the shock load and release cycle. Such comparisons can be misleading, however, and other interpretations of the data are possible. The possibility of a phase-change-like volume collapse in boron carbide under shock compression should not be ruled out.

Another intriguing feature in the velocity interferometry data of Fig. 1 should be noted. Profiles for silicon carbide are smooth and regular whereas corresponding profiles for boron carbide show an erratic and irregular component to the measured motion. The VISAR laser beam is focused to a spot of about 25-50 μm in diameter in these experiments. Consequently the measured motion represents an average over this spot size. Other workers (^{10,11}) have discussed the effect on VISAR data of differential interface motion at various spacial scales. Differential motion on a scale less than the spot size will lead to reduction in VISAR contrast because interference maxima and minima at different points within the spot will be achieved at different times. Differential motion on a scale larger than spot size will not appreciably effect contrast. Random elastic wavelets from nearby points removed from the laser spot and undergoing differential motion can, however, will lead to irregular motions at the recording point. VISAR data on both the subscale (less than spot size) and mesoscale (greater than spot size) for silicon carbide indicate homogeneous motion under shock loading. VISAR data for boron carbide, however, suggests homogeneous motion on the subscale but heterogeneous motion on the mesoscale. The latter result may suggest a heterogeneous deformation process under shock loading within the 50-500 μm spacial scale. The concentration of deformation energy into discrete deformation zones along with localized material softening or melting has been proposed as a mechanism for reduced-strength fluid-like behavior in brittle solids under shock wave load and release (¹²).

6. ACKNOWLEDGMENTS

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