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TITLE **CHARACTERIZATIONS OF SHOCK-LOADED ALUMINUM-INFILTRATED BORON CARBIDE CERMETS**

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# CHARACTERIZATION OF SHOCK-LOADED ALUMINUM-INFILTRATED BORON CARBIDE CERMETS

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Shock-recovery experiments were performed on aluminum-infiltrated $B_4C$ cermets as a function of shock pressure and composition. The effect of strain rate under uniaxial stress loading was also studied. Compressive strength was determined to be insensitive to strain rate between $10^{-3}$ and $10^{3}$ $s^{-1}$. TEM examination revealed dislocation debris and twins in a few $B_4C$ grains aftershock-loading above an upper bound HEL estimate. Below this shock pressure the $B_4C$ substructure responded elastically. Elastic moduli and strengths were highly dependent on the fraction of $B_4C$ in the cermets. However, high yield and failure strains and limited fragmentation after shock loading attest that the aluminum phase contributes significantly to the strength and integrity.

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$10^{-3}$ and $10^{3}$ $s^{-1}$. High strain rate loading was achieved with a Hopkinson split pressure bar and quasi-static testing was performed with a hydraulic testing machine. Strain was measured directly on the samples with three independent strain gages attached at equal intervals around the gage section. Strain was measured at 0.0305 and $10^{-7}$ second intervals for the quasi-static and Hopkinson bar tests, respectively.

### 3.2 Shock Recovery

Shock recovery experiments were performed using an 80 mm single-stage gas gun. Samples 18 mm dia x 3.8 mm thick were confined in a 38 mm diameter Ti-6Al-4V container with a threaded plug as described elsewhere[3]. Sample containers were "soft" recovered to preserve the shock-induced microstructure by deceleration into a water catch chamber behind the impact/projectile stripper chamber. Samples were impacted with 2.8 mm to 3.0 mm thick Ti-6Al-4V flyers to generate one microsecond pulses. Impact velocities of between 508 m/s and 1023 m/s were used to produced peak shock amplitudes of 5 GPa to 10.6 GPa in the 65% $B_4C$ cermets. Impact velocities of between 610 m/s and 1010 m/s were used to generate peak shock amplitudes of 7 GPa to 12 GPa in the 80% $B_4C$ cermet. Following shock recovery the microstructure of the cermets was characterized by TEM[3].

## 4. RESULTS

### 4.1 Compression

All of the cermets displayed a distinct yield point at about 1.3% strain (Figure 1), regardless of composition or applied strain rate. In addition, the peak strengths were not sensitive to the applied strain rate or the aluminum composition. However, deformation subsequent to the peak stress was measurably greater in the dynamic tests probably due to the faster strain sampling rate. Average peak strengths of 2200 MPa and 4200 MPa (standard

## 1. INTRODUCTION

The mechanical and microstructural response of cermets to high strain rate and shock loading is largely unknown. Studies of polycrystalline ceramics have shown that flaws can cause fragmentation at compressive shock pressures below the HEL[1]. Other studies[2] of dense, pure alumina found no microcracking after shocking up to twice the HEL. In addition, microplasticity was observed below the macroscopic HEL. The objective of this study was to investigate the microstructure and mechanical properties of tough aluminum-boron carbide cermets as a function of shock pressure, strain rate and composition. The investigation was comprised of quasi-static, dynamic (Hopkinson Bar) compression, and "soft" shock recovery experiments.

## 2. MATERIAL

A series of aluminum-infiltrated boron carbide cermets were fabricated at the Univ. of Washington. Pure liquid Al was infiltrated into $B_4C$ skeletons having densities of 65% and 80%. A 7075 Al was also used as an infiltrant for a 65% $B_4C$ cermet. The average boron carbide phase size was 6 and 18 microns for the 65% and 80% $B_4C$ cermets, respectively. The final microstructures were fully dense and consisted of two continuous phases. TEM characterization of the as-received materials[3] revealed an almost entirely defect and twin-free $B_4C$ substructure. The Al phase contained a low density of dislocations and was well bonded to the boron carbide phase

## 3. EXPERIMENTAL PROCEDURES

### 3.1 Compression Testing

Uniaxial compression tests were performed using dumb bell shaped specimens at nominal strain rates of deviation = 150 MPa) were measured for the 65% and 80% $B_4C$ cermets, respectively. Elastic moduli measured in compression and calculated from ultrasonic velocities are plotted as a function of $B_4C$ volume fraction in Figure 2. Bounding models are presented which show that the cermets generally behave as Reuss solids. The ultrasonic moduli correlate well with compression moduli when the density of the $B_4C$ alone (not the actual density) is used in the calculations. This result is consistent with the Reuss model where the aluminum contributes less than 10% to the cermet modulus. The HEL values for these cermets have not been determined by wave profile techniques; However, analogous to the elastic modulus, an upper bound HEL can be established equal to the HEL of pure $B_4C$ (15 GPa) times the volume fraction of $B_4C$. The upper bound HEL values are 9.75 GPa and 12 GPa for the 65% and 80% $B_4C$ cermets, respectively. Lower bounds for HEL, based on the yield strengths and the Poissons' ratios (determined ultrasonically), are 3 GPa and 5.5 GPa for the 65% and 80% $B_4C$ cermets, respectively. Failure strains of 1.6% were measured quasi-statically and 2.5% dynamically for the 65% $B_4C$ cermets. For the 80% B4C cermet, failure strains of about 1.35% and 2.0% were measured in quasi-static and dynamic compression, respectively. Fractography of the 65% $B_4C$ compositions show a network of microcracks intersecting the fracture surface implying that the inelastic behavior is due to damage accumulation.

### 4.2 Shock Recovery

The 65% $B_4C$ cermet samples were recovered with only limited radial cracking after shocking up to 10.6 GPa. The 80% $B_4C$ cermet was severely cracked after shocking to 12 GPa, but was not pulverized. TEM characterization of the microstructure following shock loading of the 65% $B_4C$/Al[1] revealed the response to be predominantly elastic from 8 to 10.6 GPa shocks. The boron carbide substructure displayed no evidence of plastic flow (dislocation debris) after 5 and 8.3 GPa shocks of the 65% $B_4C$-pure Al and 7075 Al cermets, respectively. Higher magnification TEM of the 10.6 GPa shocked 65% $B_4C$-pure Al sample revealed that some $B_4C$ grains contained evidence of local plastic deformation and others showed fine deformation twins and stacking faults (Figure 3). These results support the upper bound HEL value discussed above. The 65% $B_4C$-pure Al and 7075 Al cermet microstructural response to shock loading was comparable with both Al phases exhibiting uniformly distributed dislocation debris.

## 5. DISCUSSION

The elastic and compressive strength properties of the cermets are largely dominated by the fraction of $B_4C$. However, the high yield strain and permanent deformation prior to failure attest that the aluminum phase also contributes significantly to the strength and structural integrity of these cermets. The yield strain of the cermets is at least 25% higher than failure strains obtained in identically tested brittle monolithic ceramics. A comparable value of failure strain and failure mode can be achieved during compression testing of brittle ceramics by applying a modest confining pressure (100 MPa)[4]. The Reuss model assumes the applied axial stress in each phase to be equal. However, Poisson's ratio for Al is 90% greater than for $B_4C$, so that a confining pressure can be postulated to develop on the $B_4C$ substructure roughly equal to the product of: the difference in Poissons' ratios, the applied axial stress, and the volume fraction of Al assuming the Al remains elastic. A confining pressure of about 110 MPa is predicted at 2 GPa axial stress in a 65% $B_4C$ cermet. At 4 GPa axial stress a confining pressure of 130 MPa is calculated for an 80% $B_4C$ cermet. This analysis ignores many details such as plasticity in the Al, yet it demonstrates the potential for the Al phase to confine the $B_4C$ phase

In addition, once the $B_4C$ phase begins to microcrack the well-bonded Al phase can arrest the cracks and delay catastrophic failure until a network of cracks coalesce and cause final failure. The results of the "soft" recovery shock experiments similarly show that the 65% $B_4C$ cermets do not catastrophically fragment upon shock loading even at pressures above the upper bound HEL. This must be due to the tough Al phase which can arrest cracks and attenuate stress waves by plastic deformation. Above the upper bound HEL (9.75 GPa), plasticity and twins appear in a small fraction of the $B_4C$ grains. The 80% $B_4C$ cermet acts like a brittle monolithic ceramic, but it still resists complete fragmentation at shock loads equal to the upper bound HEL estimate.

## 6. CONCLUSIONS

The following conclusions can be made from compression testing: 1) Strengths and elastic properties are dominated by the cermet $B_4C$ volume fraction. 2) The Al phase appears important for several reasons: i) It may produce modest (100 MPa) confinement of the $B_4C$ substructure which results in the 25% larger yield point (1.3% strain) compared to monolithic ceramics. ii) Microcracks which develop in the $B_4C$ phase can be arrested in the Al phase resulting in substantial damage and deformation prior to failure. 3) Cermet strengths are independent of Al composition and strain rates between $10^{-3}$ and $10^{3}$ $s^{-1}$.

The following conclusions can be made based upon "soft" shock recovery experiments: 1) The boron carbide phase of the 65% $B_4C$ cermets behaves elastically up to shock pressures of 10.6 GPa. However, at this pressure dislocation activity and twins were observed in some of the $B_4C$ grains, analogous to observations expected near the HEL in monolithic ceramics. 2) Samples were recovered with limited fragmentation compared to monolithic ceramics due to the resistance of the Al phase to tensile cracking

Both Al compositions exhibited uniform plasticity at all applied shock pressures.

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FIGURE 1
Stress-strain plot of aluminum-boron carbide cermets at two strain rates.

FIGURE 2
Elastic moduli measured in compression and calculated from ultrasonic velocities versus volume fraction of $B_4C$.

FIGURE 3
Deformation twins in 65% $B_4C$ - Al after a shock of 10.6 GPa.

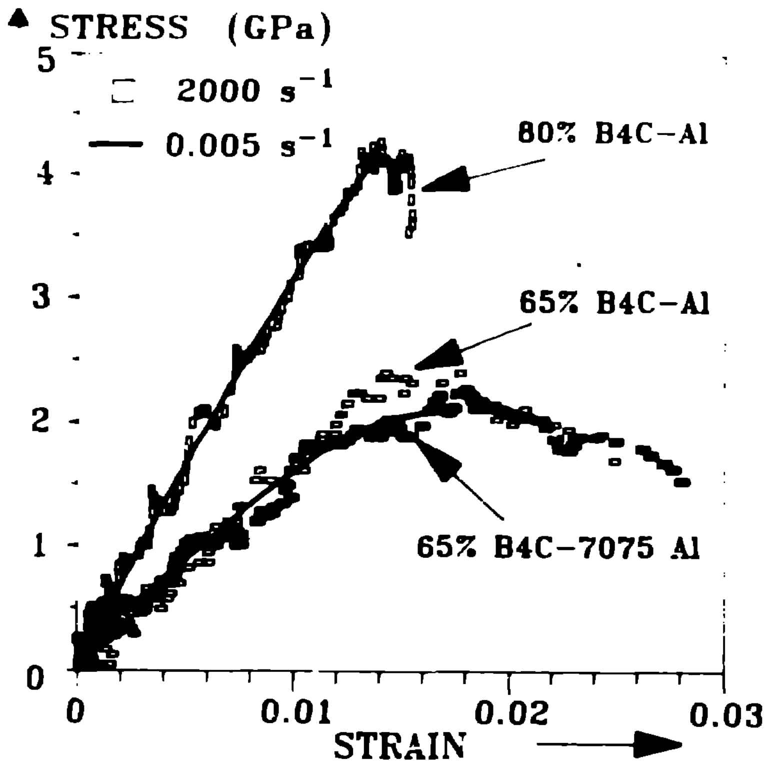


FIGURE 1

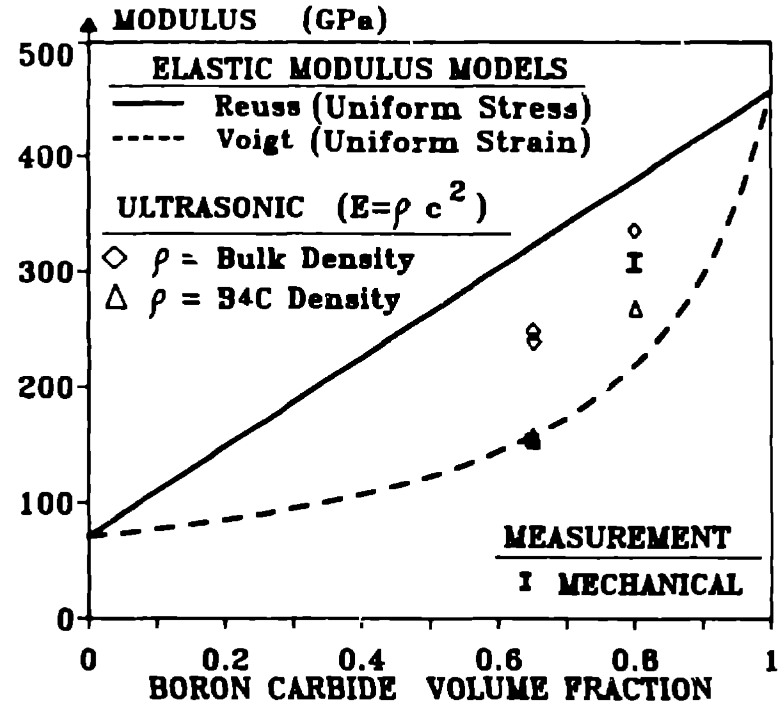


FIGURE 2

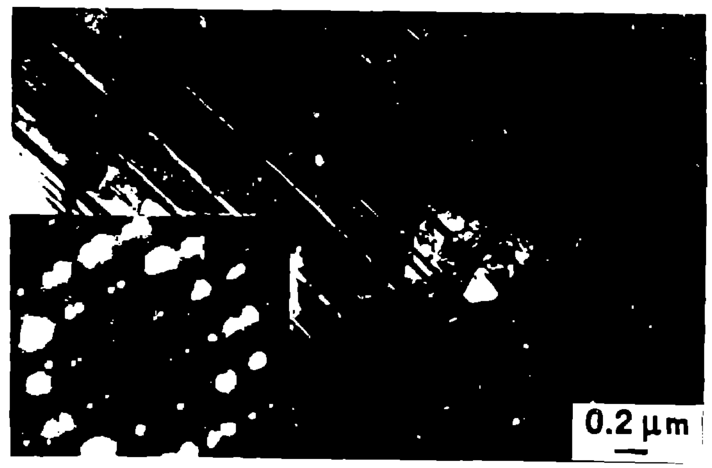


FIGURE 3