Failure Mode and Mechanism in Cermets Under Stress–Wave Loading

K. T. RAMESH, B. ALTMAN, G. RAVICHANDRAN and S. NEMAT-NASSER

Center of Excellence for Advanced Materials, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego, La Jolla, CA 92093, USA

ABSTRACT

Some preliminary results of a series of plate impact recovery experiments on boron carbide-aluminum cermets are reported. The experimental procedure is discussed, and the possible mechanisms of microcracking during loading and unloading of the specimen are explored.

KEYWORDS

Plate impact recovery test; boron carbide-aluminum cermet

1. INTRODUCTION

This is a summary of some preliminary results obtained in a series of dynamic plate impact recovery experiments performed on a class of cermets at the Center of Excellence for Advanced Materials (CEAM) of the University of California, San Diego (UCSD). One of the aims of these experiments is to understand and quantify the failure modes of ceramic composites under very short duration, high-amplitude compressive stress pulses. By limiting the pulse duration, the available energy is limited and therefore, while loading and unloading with high stress amplitudes can initiate microcracking, the overall level of damage remains limited. Hence, the samples can be recovered and evaluated, using microscopy, ultrasonics, and other characterization techniques; see related work, Kumar and Clifton (1979). Together with direct interferometric measurement of the displacement and velocity of the back face of the momentum trap (Barker and Hollenbach, 1965), this provides a powerful experimental procedure to evaluate damage initiation, damage evolution, and overall failure modes of such brittle but very strong composites under various stress pulses.

2. EXPERIMENTS

The experiments are performed using a gas gun with a 2½ inch bore, capable of attaining projectile velocities of up to 200 m/s. The projectile carries a thin flyer plate which impacts the specimen at a predetermined velocity. The flyer plate and the specimen faces are made parallel prior to impact, using an optical alignment technique; Kumar and Clifton (1977). The experiments are fully instrumented, allowing for careful measurement of the impact velocity by means of a suitably arranged set of pins, and for the displacement and velocity of the back face of the momentum trap, using interferometry; see the sketch in Fig. 1.

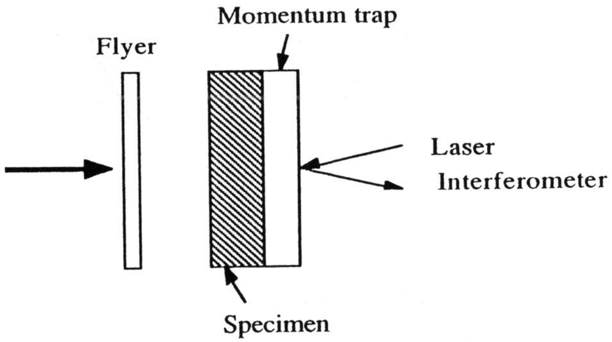

Fig. 1. Plate impact recovery experiment.

The deviation from normal impact, i.e. the tilt, is measured from the instances when the four pins, one at each corner of the specimen, contact the flyer plate. The momentum trap whose impedance matches that of the specimen, captures the pulse and carries away the tensile wave which is reflected from its back face, once this tensile wave reaches the interface between the momentum trap and the specimen. Thus the specimen can be subjected to a compressive pulse with known amplitude and duration, and then the characteristics of this pulse can be measured directly during the experiment. Furthermore, by choice of a suitable material with relatively high yield stress for the momentum trap, and by limiting the impact velocity, it is assured that no plastic flow occurs in the momentum trap, and therefore, changes in the stress pulse measured at the back face of the momentum trap can be used to assess the nature of the damage that it has produced in the specimen.

A gap can be provided between the momentum trap and the specimen, which then produces a short tensile pulse of a duration corresponding to the time required for the closure of the gap. This pulse travels back as a release pulse and subjects a small region near the impact face of the specimen to tensile loading. By controlling the gap size, we can control the thickness of the region which subsequent to the initial compression loading and unloading, has also experienced tensile loading. A typical X-t diagram for the plate impact recovery test is shown in Fig. 2, including the effect of the small gap between the momentum trap and the specimen interface. Upon impact, compressive waves travel through the specimen and the flyer plate. When the pulse reaches the gap, it is reflected as a tensile pulse, until the gap is closed, at which time the compression pulse continues to travel into the momentum trap. The compression pulses traveling in the flyer plate and momentum trap are each reflected back as tension waves, and when they reach the interface with the specimen, the flyer plate and the momentum trap are separated from the specimen. The short duration release pulse due to the gap travels back in the specimen and can subject a small region of the specimen close to the impact face to a short duration tensile pulse. This pulse reflects back as a compression pulse and, after traveling through the specimen behind the main compression pulse, it is transmitted to the momentum trap and is recorded through interferometric measurement. It may provide the means for assessing the damage level in the specimen.

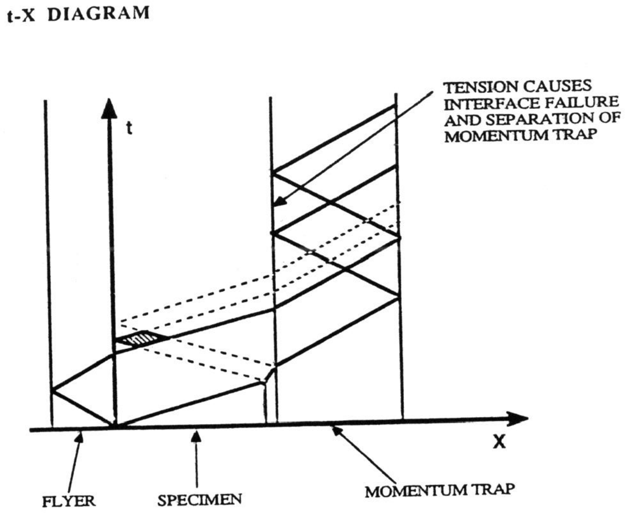

Fig. 2. The X-t diagram corresponding to the plate impact recovery experiment, including the effect of the presence of a small gap between the specimen and the momentum trap.

3. MATERIALS

The specimens are made of a class of cermets of 55% volume fraction boron carbide and 45% aluminum, provided by the Lawrence Livermore National Laboratory. The material is processed using an infiltration procedure, Halverson *et al.* (1986). The boron carbide particles, with sizes ranging from 0.5 - 2.0 μm, are compacted and chemically treated. The compacted aggregate is then infiltrated with molten 7075 aluminum. The resulting composite is heat treated at about 1,000°C for several hours. The density of the composite is 2,560 kg/m^3, and has a hardness of about 1,400 kg/mm^2 on the Vicker scale. The ultrasonically measured longitudinal and shear wave speeds are 11.7 mm/μs and 7.2 mm/μs, respectively. The specimens are 25 mm squares of about 6 mm thickness.

The flyer plate and the momentum trap are made of a Ti-6Al-4V alloy. The acoustic impedance of this material is within 5% of that of the cermet. The flyer plate is also 25 mm square and about 1.5 mm thick, resulting in a loading pulse of about 0.5 μs in duration. The Ti-6Al-4V momentum traps are elctroplated with a 25 μm thick layer of nickel at the rear surface, to facilitate the interferometric measurements.

4. RESULTS AND DISCUSSION

Data corresponding to four tests are summarized in Table 1, where U_0 is the impact-velocity, σ_0 is the stress amplitude, and t_L is the pulse duration. Figure 3 shows the resulting particle velocity measured at the rear surface of the momentum trap for the experiment designated by BA-14 in Table 1.

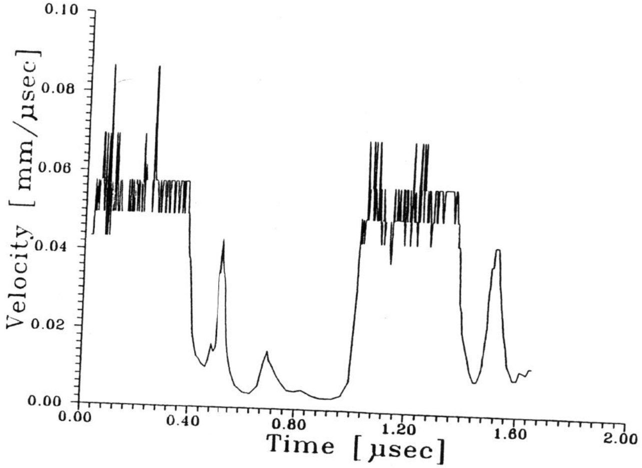

Fig. 3. Measured velocity profile at the back face of the momentum trap.

sequences. These may include: (1) microcracking due to initial compression by the primary pulse; (2) microcracking due to unloading and reloading, as the tensile pulse travels back along the specimen; (3) tensile cracking, as the reflected tensile pulse crosses the primary compression close to the impact face of the specimen; (4) microcracking caused by the unloading of the primary compression pulse; and, finally (5) additional microcracking due to loading and unloading, as part of the short tensile pulse reflects back from the impact face or the fractured region close to the impact face, as a short compression pulse with a reduced amplitude. It is reasonable to expect that most of the energy of the short tensile pulse is actually lost in the process of tensile cracking close to the impact face.

Figures 4a,b are micrographs showing the damage in the main part of the specimen (Fig. 4a), and close to the impact face (Fig. 4b). The axial crack seen in Fig. 4a typifies cracks observed in axial compression of heterogeneous brittle solids; see Horii and Nemat-Nasser (1985,1986).

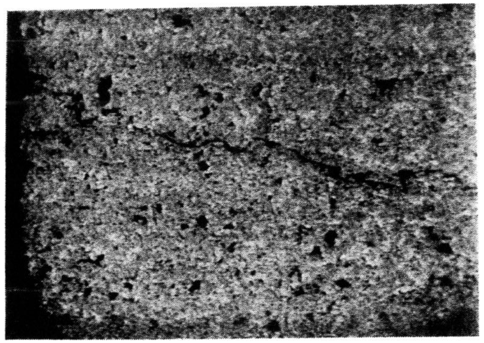

Fig. 4a. Micrograph of recovered specimen; disintegrated boron carbide particles are connected by axial microcracks.

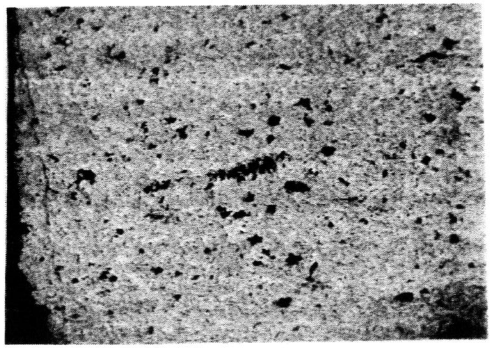

Fig. 4b. Micrograph of recovered specimen; tensile cracks parallel to the impact face, produced by the short tensile pulse which is reflected from the gap between the specimen and the momentum trap.

Table 1. Summary of experimental conditions

Experiment	Uo m/s	σ_o MPa	t_L μs
KT-11	45	600	0.47
KT-12	60	800	0.50
BA-14	58	770	0.44
BA-15	71	950	0.43

The specimen in this test was recovered with no visible damage. In this test the measured width of the compressive pulse was about 0.4 μs which is less than 0.44 μs which is the value expected in the absence of any gaps. The compression pulse was followed by a short pulse of width of about 0.05 μs and of considerably smaller amplitude. This pulse corresponds to the reflected tensile pulse due to the presence of a gap between the specimen and the momentum trap. This tensile pulse propagates back along the sample and causes unloading and then reloading, as it moves toward the impact face. Once it crosses the tail of the incoming primary pressure pulse, it subjects the sample to tension which can produce additional damage and cracking parallel to the impact face.

Thus, except for a small region close to the impact face, most of the sample is subjected to the following sequence of loading and unloading: (1) compression due to the incoming primary pulse; (2) unloading due to a tensile pulse reflected from the gap between the specimen and the momentum trap; (3) recompression as the tensile pulse moves toward the impact face of the specimen and the gap closes; (4) unloading as the tail of the primary compressive pulse moves along the specimen and into the momentum trap; (5) reloading, as the short tensile pulse is reflected as a compression pulse from the impact face, or the free surface of tension cracks that may have been formed very close to the impact face; and finally (6) unloading, as this short compressive pulse traverses the specimen and moves into the momentum trap.

The region close to the impact face of the specimen experiences the first four loading and unloading sequences, but as the short tensile pulse crosses the tail of the primary compression pulse, it subjects this region to tensile stresses which produce tensile cracks parallel to the impact face of the specimen.

Had the sample remained fully elastic, with no damage whatsoever, the reflected tensile pulse would travel back along the sample, would reach the interface with the flyer plate and the specimen, would be reflected as a compression pulse with equal amplitude, would travel back along the sample toward the momentum trap as a compression wave, and would be transmitted to the momentum trap to be measured as a compression pulse of an amplitude equal to the primary compression pulse. The reduction in the amplitude of this pulse in actual tests is due to a complex set of possible microcracking

It consists of disintegrated zones within the boron carbide that are connected by microcracks. Since the boron carbide matrix consists of compacted particles of 0.5-2 μm size, it may undergo microcracking, both parallel to the direction of loading during compression and perpendicular to this direction during removal of the compressive stress. Since each particle within this region of the specimen undergoes three compressive loadings and three unloadings, it is reasonable to expect that compressed aggregates of boron carbide may disintegrate, forming regions containing fragmented boron carbide.

ACKNOWLEDGEMENT

This work has been supported by the U.S. Army Research Office under Contract No. DAAL-03-86-K-0169 to the University of California, San Diego. The authors thank the Chemistry and Materials Science Department of the Lawrence Livermore National Laboratory for providing the boron carbide-aluminum samples.

REFERENCES

Barker, L. B. and R. E. Hollenbach (1965). Interferometer technique for measuring the dynamic mechanical properties of materials. *Rev. Sci. Instr.*, 36, 1617-1620.

Halverson, D. C., A. J. Pyzik, I. A. Aksay, and W. E. Snowden (1986). Processing of boron carbide-aluminum composites. Lawrence Livermore Laboratory, Technical Report, UCRL-93862, 1-9.

Horii, H. and S. Nemat-Nasser (1985). Compression-induced microcrack growth in brittle solids: Axial splitting and shear failure. *J. Geophys. Res.*, 90, 3105-3125.

Horii, H. and S. Nemat-Nasser (1986). Brittle failure in compression: Splitting, faulting and brittle-ductile transition. *Phil. Trans. Roy. Soc. of London*, A-319, 337-374.

Kumar, P. and R. J. Clifton (1977). A star-shaped flyer for plate impact recovery experiments. *J. Appl. Phys.*, 48, 4850-4852.

Kumar, P. and R. J. Clifton (1979). Dislocation motion and generation in LiF single crystals subjected to plate impact. *J. Appl. Phys.*, 50, 4747-4762.