Micromechanics of Dynamic Fracturing of Ceramic Composites: Experiments and Observations

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ABSTRACT

The conventional compression split Hopkinson bar is modified for application to dynamic testing of very hard materials such as ceramics and ceramic composites. The technique is used to study the response and failure modes of boron carbide-aluminum cermets. The effects of heat treatment on the dynamic response of this cermet are examined.

KEYWORDS

Micromechanics; Hopkinson bar; cermets

1. EXPERIMENTAL TECHNIQUE

A new experimental technique for high strain rate testing of ceramics and ceramic composites based on a modified split Hopkinson bar is described in this paper. Results are presented for a boron carbide-aluminum cermet. Microscopic observations of fractured materials reveal failure modes corresponding to high strain rate behavior of these ceramic composites.

1.1. Conventional Approach

In the conventional compression split Hopkinson bar a specimen is sandwiched between two elastic bars, respectively called the incident bar and the transmission bar, as sketched in Fig. 1. The striker bar hits the incident bar at end A, sending a compression pulse along the incident bar. The pulse duration equals twice the travel time of the elastic bar wave in the striker bar; see Follansbee (1985).

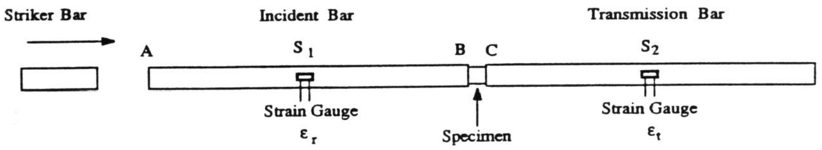

Fig. 1. The schematic of the conventional compression split Hopkinson bar.

When the pulse reaches the specimen which is placed between the end B of the incident bar and the end C of the transmission bar, part of the pulse reflects back and the remaining part is transmitted through the specimen to the transmission bar. The strain gauges at points S_1 and S_2 provide time-resolved measures of the signals. The stress levels in the bars are kept sufficiently low, so that the bars remain elastic. The specimen then undergoes dynamic elastic-plastic deformations. From the reflected signals the axial strain in the specimen is estimated, and the transmitted pulse provides a measure of the axial stress in the specimen. The initial part of the stress-strain relation is often neglected, since the stress state in the sample is inhomogeneous initially. Since the stress pulse excites both axial and radial particle displacements, corrections based on elastic waves in cylindrical bars can be incorporated in interpreting the results.

In the usual application of the compression split Hopkinson bar, the reflected pulse is tensile, since, in general, the specimen is much more compliant than the bars. Elementary calculations then show that the strain rate in the sample, $\dot{\varepsilon}_s$, can be estimated from

$$\dot{\varepsilon}_s = -\frac{2c_o}{\ell}\,\varepsilon_r\,, \qquad (1)$$

where ℓ is the length of the sample, ε_r is the time-dependent reflected strain, and c_o is the bar wave velocity in the incident bar. The axial stress in the sample, σ_s, is estimated from

$$\sigma_s = \frac{1}{2}\,E_t\,\frac{A_t}{A_s}\,\varepsilon_t\,, \qquad (2)$$

where A_s is the area of the cross section of the sample, and ε_t is the time-dependent strain in the transmission bar whose area is A_s and whose Young modulus is E_t; see Kolsky (1949).

For the apparatus to function as designed, the yield stress and the stiffness of the sample must be considerably smaller than the yield stress and the stiffness of the bars. The ends B and C of the bars then remain essentially flat as the specimen shortens axially and expands radially.

1.2. Modified Compression Split Hopkinson Bar for Dynamic Testing of Ceramic Composites

When very hard materials such as a boron carbide-aluminum cermet (B_4C-Al), or other very hard ceramic composites are being tested in the compression split Hopkinson bar, many serious problems are encountered. They include: (1) the ends of the incident and transmission bars do not remain flat as the hard sample indents into them (see sketch in Fig. 2); and (2) the compression pulse is reflected most often as compression and sometimes transmitted completely through the sample with little reflection. Therefore, it is not possible to use the reflected wave for estimating the strain rate in the sample. On the other hand, the transmitted pulse is still a good measure of the stress in the sample.

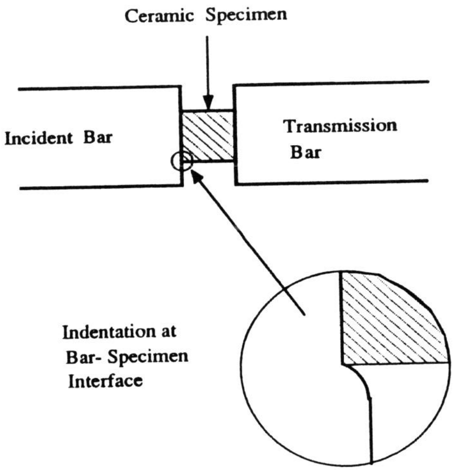

Fig. 2. Indentation at bar-specimen interface during testing of hard ceramic samples in a compression split Hopkinson bar.

We have modified the conventional compression Hopkinson bar for application to dynamic testing of ceramics and ceramic composites which, in general: (1) are extremely hard; and (2) undergo very little strain prior to failing. This new technique involves two essential changes:

1) a thin copper plate is glued to the end A of the incident bar;
2) the strain is measured directly by attaching strain gauges to the sample.

The presence of the copper plate introduces a monotonically increasing ramp-like stress pulse in the incident bar. While this limits the strain rates at which the test can be performed, it does preclude sudden straining of the sample. Figure 3a illustrates the stress pulse profile produced by the conventional compression split Hopkinson bar, using a uniform striker bar.

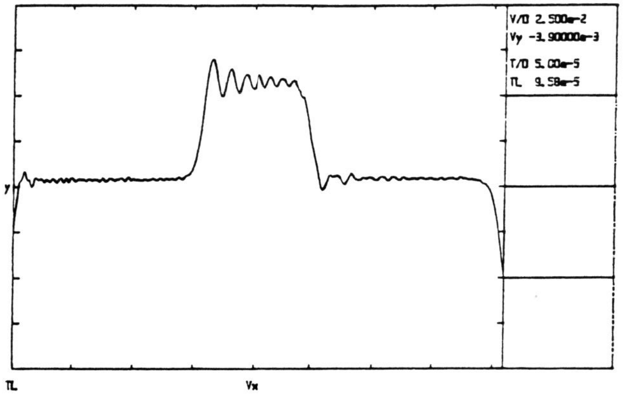

Fig. 3a. Stress pulse produced in the conventional split Hopkinson bar by a uniform striker bar.

The pulse has a sharp rise and a sharp fall. This results in a step loading of the specimen which is suddenly held at a strain corresponding to the step pulse. Even if the sample fails, it is very difficult to estimate the strain rate and the strain of the sample, and to characterize the test and the material response.

To produce a ramp rise and a ramp fall in the pulse, an appropriately tapered striker bar and proper cushioning of the end A of the incident bar are incorporated. This leads to the stress pulse illustrated in Fig. 3b.

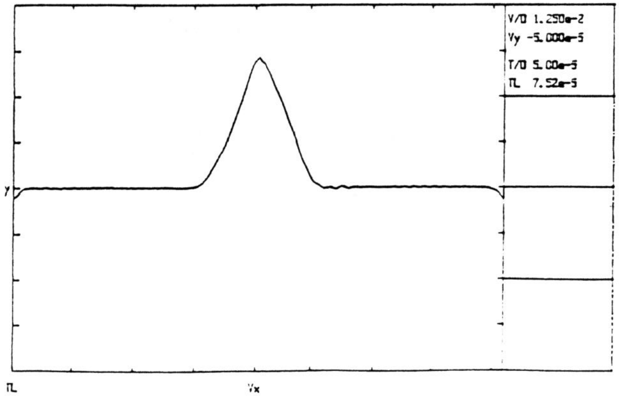

Fig. 3b. Ramped pulse produced by tapered striker bar and ¼" copper cushion piece.

In the present study a tapered bar and a ¼ in. copper plate cushion have been employed, as illustrated in Fig. 4.

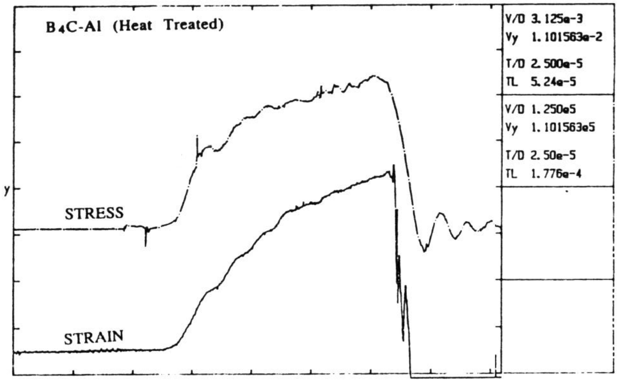

Fig. 4. Stress and strain in heat treated B_4C-Al specimen, produced by the new technique.

As shown in Fig. 4, the sample strain is measured directly by placing a strain gauge on the sample. Thus in this approach the stress in the sample is obtained by recording the transmitted pulse and the strain by direct measurement. Note that both the axial and the lateral strains can be measured by placing suitably oriented strain gauges on the sample.

2. MATERIAL AND EXPERIMENTAL RESULTS

2.1 Material

The material used in this experiment is a boron carbide-aluminum cermet consisting of grains of pressed boron carbide particles, and aluminum. The boron carbide grains are 10-20 μm in diameter, consisting of boron carbide particles, 0.5-2 μm in diameter, which are chemically pressed; see Halverson *et al.* (1986). Table 1 summarizes the physical properties of the cermet and the corresponding Vickers hardness. Upon heat treatment at 1,000°C, the aluminum phase of the composite interacts with boron and carbon, forming intermetallic compounds. The resulting heat treated cermet has considerably different mechanical properties, dynamic response, and failure modes than the untreated boron carbide-aluminum. The specimens used in Hopkinson bar testing were about 9 mm in diameter and 9 mm long.

Table 1. Physical properties of the B_4C-Al cermet

Material State	Density kg/m^3	Vickers hardness kg/mm^2	Longitudinal wave speed m/s	Shear wave speed m/s
As infiltrated	2,560	1,100	9,600	6,000
Heat-treated	2,560	1,400	11,700	7,200

2.2 Experimental Results

Figure 5 is a typical result for the heat treated boron carbide-aluminum

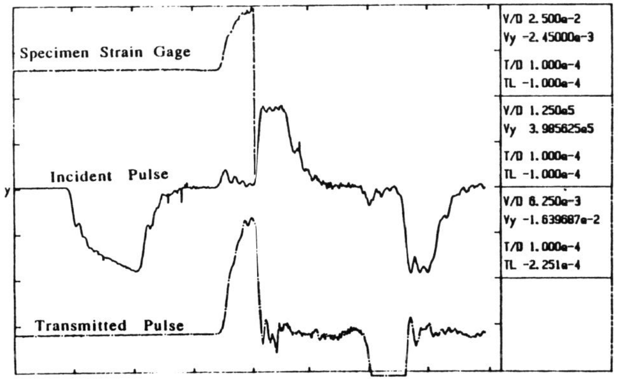

Fig. 5. Typical results for the heat treated B_4C-Al specimen which failed during compression loading.

sample which failed during compressive loading. Failure is marked by the interruption in the strain gauge reading. In this test the incident pulse has essentially a ramp profile. Figure 6 shows the stress-strain relation for the sample which has disintegrated at failure.

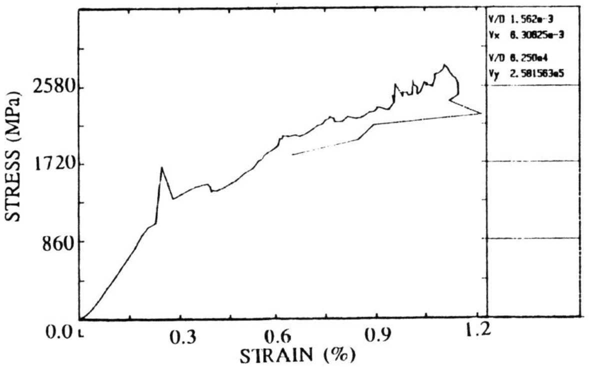

Fig. 6. Stress-strain curve for heat treated B_4C-Al cermet.

It is a bilinear curve, with an initial, essentially elastic, stress-strain relation with a modulus of about 420 GPa, followed by a more compliant response corresponding to a reduced modulus of about 165 GPa. The axial stress and strain at failure respectively are, 2,800 MPa and 1.18%. Figure 7 shows the stress-strain curve for the boron carbide-aluminum cermet which has not been subjected to heat treatment, i.e. *as infiltrated*.

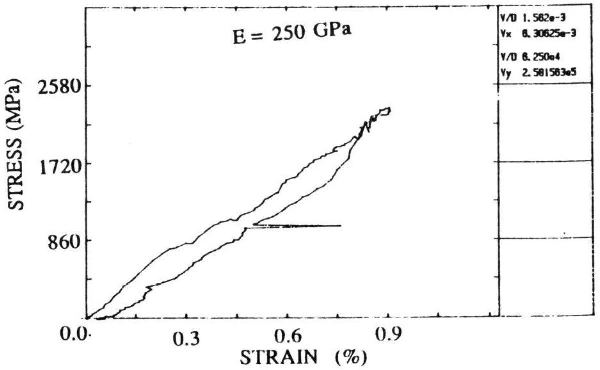

Fig. 7. Stress-strain curve for as infiltrated B_4C-Al cermet.

In this case, the specimen splits axially, but continues to transmit the axial stress, while the strain gauge remains attached to the specimen. Hence, it is possible to obtain complete loading and unloading, as shown in the figure. Figures 8a,b are the SEM graphs of the surfaces of the failed specimens.

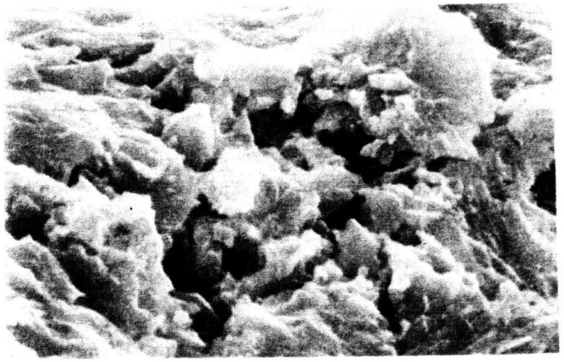

Fig. 8a. A typical SEM micrograph of the surface of the failed heat treated B_4C-Al cermet.

Fig 8b. A typical SEM micrograph of the surface of the failed *as infiltrated* B_4C-Al cermet.

Figure 8a corresponds to the heat treated specimen, and Fig. 8b to the *as infiltrated* specimen. The heat treated specimen fails by cleavage cracking of the boron carbide and the intermetallics, with the final failure involving decohesion of the boron carbide particles and the disintegration of the boron carbide aggregates. The as infiltrated sample shows ductility and fails by cleavage cracking of boron carbide aggregates and void growth in the aluminum phase. The aluminum ligaments tend to bridge the cracks in the boron carbide.

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