AN ULTRASONIC EVALUATION OF DAMAGE IN CERMETS

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INTRODUCTION

Cermets are hard ceramic-metal composites with predominant ceramic phases and are finding increasing applications. It is important to understand the evolution of damage and the failure modes in these materials under dynamic loading conditions in order to design them for impact resistant applications. In this investigation a plate impact recovery technique [1,2] is used to subject cermet specimens to a single step compressive pulse of known amplitude and duration. This technique has the advantage of applying sufficiently high stress levels to initiate damage and yet providing controlled amounts of energy input to avoid catastrophic failure of the material. Ultrasonic velocity and attenuation studies are carried out on the recovered specimens to asses the evolution of damage under stress wave loading. Optical microscopy and image processing techniques are used to quantify the extent of damage in the recovered samples. Techniques such as ultrasonic measurements could prove to be useful in predicting damage levels in materials subjected to dynamic loading. The material chosen for study is a boron carbide-aluminum cermet [3].

EXPERIMENTAL PROCEDURES

The experiments are performed using a plate impact recovery technique [1,2]. The experiments are fully instrumented and very well characterized allowing an unambiguous interpretation of the measurements. The experimental configuration is shown in Fig. 1. A thin flyer plate impacts a target made of the material under investigation. The flyer plate is aligned parallel to the specimen face prior to impact using an optical technique [4]. The impact velocity is obtained from measuring the times at which five sets of pins that are spaced at known distances apart are shorted by the projectile. The deviation from normal impact (tilt) is assessed by measuring the times at which four pins on the face of the specimen are shorted by the flyer. An impedance matched momentum trap is attached to the rear of the specimen so that the principal loading pulse does not reflect from the rear surface and reload the specimen. The compressive loading pulse that propagates through the specimen propagates through the momentum trap and reflects from the stress free rear surface of the momentum trap as a tensile wave. When this tensile pulse arrives at the specimen-momentum trap interface, the interface fails and the momentum trap separates. The thickness of the momentum trap is chosen such that the entire loading pulse is trapped within it.Thus the specimen can be recovered after having been subjected it to a single plane compressive step pulse of known duration t_L determined by the round trip time of a longitudinal wave in the flyer. Flyer and momentum trap materials are selected to remain elastic under the conditions of the test. All

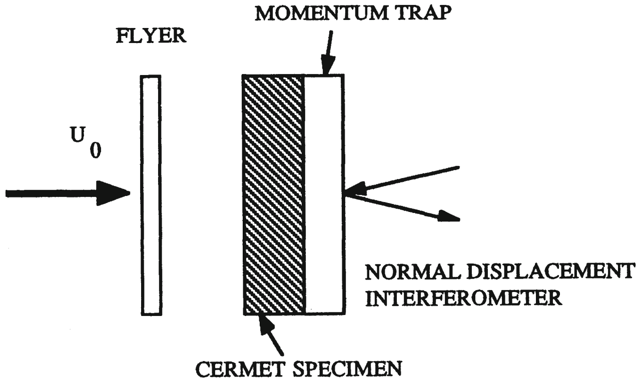


Fig. 1. Schematic of the experimental configuration

interfaces are lapped flat and aligned parallel so as to permit a plane wave interpretation of the experiment. The particle velocity at the rear surface of the momentum trap is measured using a normal displacement interferometer [5].

The plate impact recovery experiment is best understood in terms of the time-distance diagram (t-X) shown in Fig. 2. This figure shows the wavefronts propagating through the flyer, the specimen, and the momentum trap. The t-X diagram as drawn in Fig. 2 shows the actual experimental conditions; a gap exists between the specimen and the momentum trap. This results in a short tensile pulse, the duration of which corresponds to the time taken for the closure of the gap. This tensile pulse propagates back into the specimen and is trapped within the momentum trap. This specimen has been subjected to a compressive pulse followed by a short tensile pulse. However, only a small region near the impact face is subjected to a state of tension, shown as a shaded area in Fig. 2.

The amplitude of the input step pulse σ_0 is given by:

$$\sigma_0 = \frac{1}{2}\rho c_L U_0$$

where ρ is the mass density, c_L is the longitudinal wave speed, and U_0 is the impact velocity. The amplitude of the input stress pulse can be controlled by changing the impact velocity. It is assumed that there is no mismatch in the acoustic impedances (ρc_L) of the flyer, the specimen, and the momentum trap.

The specimens are subjected to ultrasonic velocity and attenuation measurements before and after the experiment using a pulse echo technique.All the ultrasonic measurements are carried out using a Matec MBS-8040 system. The recovered specimens are cut with a high speed diamond saw, polished and then examined using an optical microscope which is coupled to a digital image processing system.

MATERIALS

The cermet which is chosen for this study is a 55 vol % boron carbide- 45 vol % aluminum cermet obtained from the Lawrence Livermore National Laboratories. The material is prepared by an infiltration process [3]. The boron carbide particles (sizes ranging from

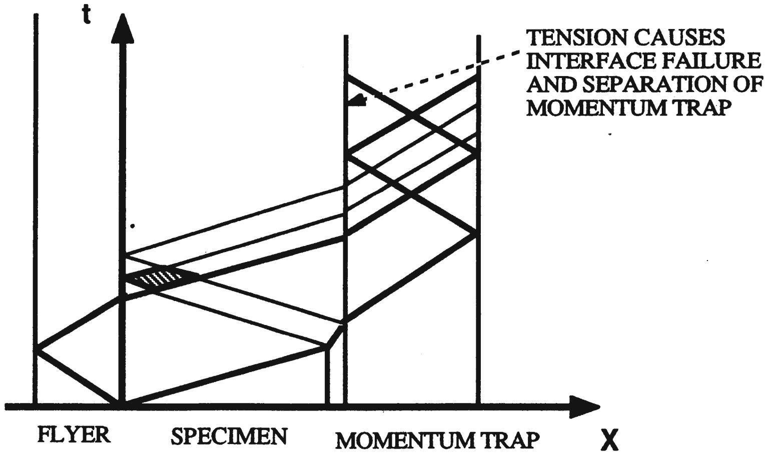


Fig. 2. Time-distance diagram for the recovery experiment

0.5-2.0 μm) are compacted together and treated chemically. This compacted aggregate is then infiltrated with molten 7075 aluminum. The composite is then heat treated at about 1000 °C for several hours. The density of this material is 2560 kg/m^3; it has a hardness of about 1400 kg/mm^2 on the Vickers scale. The longitudinal and shear wave speeds measured for this material using ultrasonics are 11.7 mm/μs and 7.2 mm/μs respectively. The specimens are 25 mm squares, each about 6 mm thick.

The flyer 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 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 electroplated with a 25 μm thick layer of nickel at the rear surface to facilitate the interferometric measurements.

RESULTS

Stress Wave Profiles

The results from three preliminary experiments on the boron carbide-aluminum cermet are described here. The summary of the experimental results from the three tests and the properties of the unimpacted material is shown in Table I. The amplitude of the input step stress pulse ranged from 560 MPa-1250 MPa; the pulse duration is about 0.5 μs. The resulting particle velocity measured at the rear surface of the specimen for one of the experiments (KT-11; impact velocity=45 m/s) is shown in Fig. 3. The specimen from this experiment is recovered with no visible damage. If the specimen remained elastic during the test, the resulting incident compressive pulse would be a step pulse, with a rear surface particle velocity of constant amplitude equal to the impact velocity. The pulse width would then correspond to the round-trip time of the longitudinal wave in the flyer (assuming no gap exists). Fig. 3 shows that the initial compressive pulse reaches the expected amplitude but the pulse width (0.35 μs) is less than the expected value, namely 0.47 μs. The compression pulse is followed by a pulse of width of about 0.15 μs but of considerably smaller amplitude. This is the tensile pulse that propagated back in to the specimen due to the gap between the

Table I. Summary of experimental results

Shot	Uo m/s	σ_0 MPa	t_L μs	Damage	c_L mm/μs	c_S mm/μs
Before Impact	—	—	—	0.01	11.7	7.2
KT-11	45	600	0.47	—	11.6	6.7
KT-12	60	800	0.50	0.05	11.2	6.5
KT-13	100	1350	0.47	0.13	10.9	6.2

momentum trap and the specimen. This gap is estimated to be about 5 μm. We note that the tensile pulse that propagated through the specimen has an amplitude of about half that of the original pulse.

Evaluation of Damage

Measurements are made of the longitudinal and the shear wave velocities in the recovered specimens, and their variation with the applied stress level. The ultrasonic velocity measurements demonstrate a trend in the wave velocities (both longitudinal and transverse) decrease with increase in applied stress level. The percentage change in the transverse velocity is typically more than that for the longitudinal velocity for a given stress level. Plots of the wave velocities as a function of the applied stress level are shown in Figures 4(a) and 4(b).

Quantitative optical microscopy is used to measure damage in the material. The recovered specimens are sectioned and polished and then examined in an optical microscope. Optical micrographs of a specimen that has not been impacted and of a sample that has been

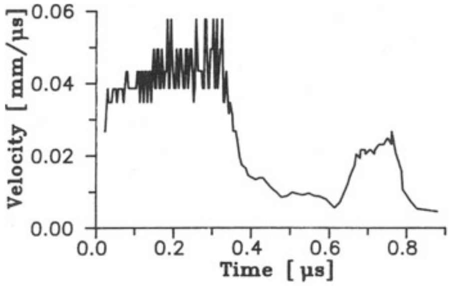


Fig. 3 Free surface velocity-time profile for shot KT-11; impact velocity = 45 m/s

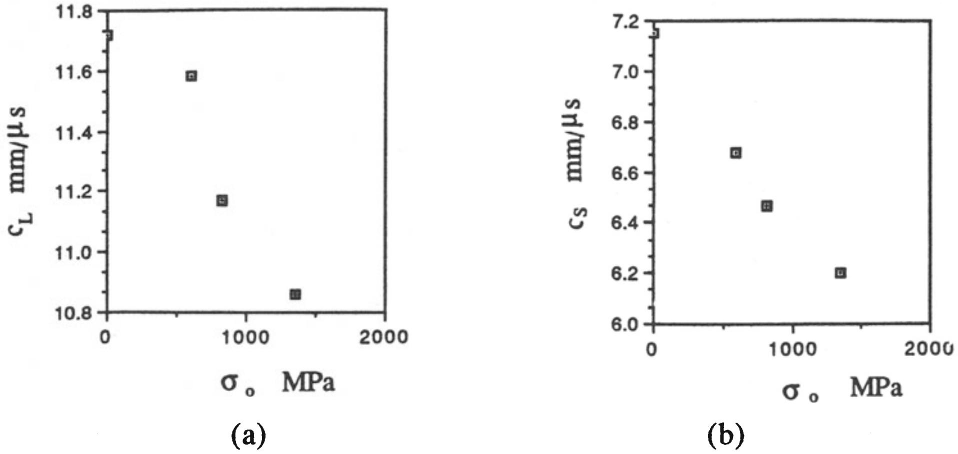
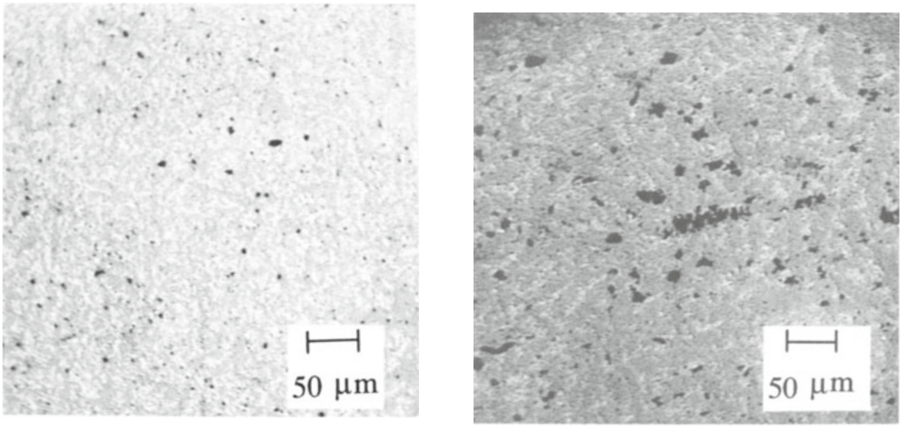


Fig.4. (a) Longitudinal velocity c_L as function of applied stress level σ_o
(b) Shear wave velocity c_S as a function of applied stress level σ_o

subjected to a pulse of amplitude 1200 MPa and about 0.5 μs duration are shown in Figures 5(a) and 5(b). Both the specimens are prepared using identical procedures. The regions that appear dark and void-like are considered to be regions of damage. A visual inspection of the micrographs show the amount of damage in the impacted specimens when compared to the virgin material. The micrographs are then analyzed using an image processing system using which the area fraction and hence the volume fraction of damaged zones can be computed. It is observed that the area fraction of damaged zones also increases with increasing input stress level; see Table I. Both microcracks and extended cracks are observed in the recovered specimens. Cracks occur both along and transverse to the direction of loading. Transverse cracks occur only near the impact faces whereas the axial cracks occur throughout the cross section. Microcracks run essentially through the boron carbide phase, and are bridged by the intermetallic phases.



(a)
(b)

Fig. 5. (a) Micrograph of the material prior to impact
(b) Micrograph of the recovered specimen KT-13

DISCUSSION

From the preliminary results obtained for damage evolution in heat treated boron carbide-aluminum cermets using the plate impact recovery technique, it appears that the initial compression pulse causes very little damage in the material. This can be deduced from the fact that the compression pulse from the interferometric measurements is nearly a step pulse with the expected amplitude, i.e. the rear surface particle velocity approximates the impact velocity. During the initial compression most of the strain is presumed to be accommodated by the relatively soft intermetallic phases. It is believed that when the compression pulse is unloaded by the reflected wave, residual strains due to the intermetallic phase can cause failure of the boron carbide matrix, generating damage zones. The tensile pulse that propagated through the specimen has a much smaller amplitude, suggesting that the loss of energy of this pulse may be due to the damage evolution in the material. A small gap between the momentum trap and the specimen produced a short tensile pulse.This pulse may cause the damage to develop further by causing the decohesion within the damage zones near the impact face.

The dark regions that appear in the micrographs should not be interpreted as voids, but rather as regions of decohesion of boron carbide particles; these particles are pulled during the specimen preparation process (polishing) generating the appearance of void like structure. These regions are termed damage zones. The average size of the individual damage zones are of the size of about 0.5-2 μm, which is also the size of the individual boron carbide particles with which the initial aggregate is made. This suggests that the boron carbide matrix is disintegrating, a possible mechanism for final failure. The micrographs also show that the damage zones are often clustered, and that they link together to form microcracks; see Fig. 5(b). The microcracks may then link up to form extended cracks that are either axial or transverse, depending on the local dominant stress state.

Within the material the damage zone is likely to be a void containing a packed collection of boron carbide particles. Such zones would transmit some compressive stress but would be less capable of sustaining a shear stress. This would explain the greater sensitivity to shear than to compression that is observed in the ultrasonic measurements; see Figures 4(a) and 4(b).

Efforts to extend this work include ultrasonic attenuation measurements as a function of frequency, and the measurements of the variation of the attenuation with applied stress level. The micromechanisms of damage in boron carbide-aluminum cermets will be further investigated with the aid of scanning electron microscopy. Efforts are also underway to develop micromechanical models for the evolution of damage in cermets through further experiments and analysis.

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