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The effects of defects on the uniaxial compressive strength and failure of an advanced ceramic

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ABSTRACT

This study investigates the effects of the processing-induced defect population on the dynamic compressive strength and failure of a hot-pressed boron carbide. Quantitative microscopic analysis was used to determine the distributions of three types of processing-induced inhomogeneities: aluminum nitride, small graphitic particles and pores, and larger graphitic disks. Scanning electron microscopy of fracture surfaces identifies the graphitic disks as fracture initiation sites. The size, orientation and number density of the graphitic disks are then quantified using image processing techniques. We use these defect statistics, in conjunction with recent scaling models, to explore our experimentally measured dynamic compressive strength results.

1. Introduction

Designing new advanced ceramic materials for protective systems requires a fundamental understanding of high-rate failure mechanisms, and of the effects of microstructure on these mechanisms. The dynamic behavior of several advanced ceramics has been investigated (e.g., silicon carbide [1,2], aluminum nitride [3], titanium diboride [4]) in terms of mechanisms such as dislocation activity [3], amorphization [5] and fracture and fragmentation [6]. In this study, we extend previous works on dynamic brittle failure in ceramics by investigating the links between the defect population and the uniaxial compressive strength and failure of a commercially available hot-pressed boron carbide.

The compressive failure of brittle materials is generally a result of the initiation, propagation and coalescence of cracks originating from defects (such as grain boundaries, inclusions, pre-existing micro-cracks and surface flaws). During quasi-static compression, a small number of relatively large flaws (or ‘defects’- used interchangeably throughout) are activated and the resulting crack growth rate leads to rapid structural failure. During dynamic compression, the rate of loading is too large to be relaxed by crack growth of a few relatively large activated flaws. This results in the activation of additional, smaller defects, and this process also manifests as an increase in strength for increased rates [7–10].

The rate-sensitivity of the compressive strength of brittle materials has been shown to be strongly dependent on defect distributions [9,11–13]. For example, a model developed by Paliwal and Ramesh [11] coupled the initial defect distribution, the dynamics of crack growth and crack–crack interactions, considering flaw size and flaw number density. Recent work by Hu et al. [12] extended this formulation to include anisotropic damage and the effect of flaw orientation on the dynamic failure of brittle materials. Graham-Brady [13] extended the work of Paliwal and Ramesh [11] to include the effect of the localized flaw density on the dynamic compressive failure of brittle materials. More recently, Kimberley et al. [9] developed a scaling relation to describe the rate-dependent compressive strength of brittle materials that incorporates the interaction of a distribution of preexisting flaws and crack growth dynamics. Their analytical model was shown to provide reasonable agreement with simulation results using the Paliwal and Ramesh [11] model.

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In this paper, we examine the links between the microstructure and the dynamic uniaxial compressive strength and failure of a hot-pressed boron carbide. We give particular attention to characterizing the defect populations (e.g., size, orientations and flaw density) and linking these with strength measurements. We then incorporate the defect statistics into the scaling relation developed by Kimberley et al. [9] to explore its applicability to boron carbide, including our hot-pressed material and a pressureless sintered material studied previously by Sano et al. [14].

2. Experimental setup

Quasi-static and dynamic uniaxial compression experiments were performed on a hot-pressed boron carbide from Coorstek (Vista, California), with a Young's modulus of 430 GPa, a density of 2510 kg/m^3, and a Poisson ratio of 0.16–0.17 (as determined by the manufacturer). The boron carbide material was received as tiles (conceptualized in Fig. 1a) with dimensions of 305 mm in length, 254 mm in width, and 8 mm in thickness. Experiments were performed by loading sectioned specimens both parallel (termed “through-thickness”: TT) and normal (termed “in-plane”: IP) to the plate thickness, which is the hot-pressing direction (Fig. 1a). The cuboidal specimens used in the compression tests were 5.3 mm in length, 3.5 mm in width and 4.0 mm in height. These are conceptualized on the right in Fig. 1a. The use of cuboidal specimens allows visualization of failure during dynamic loading.

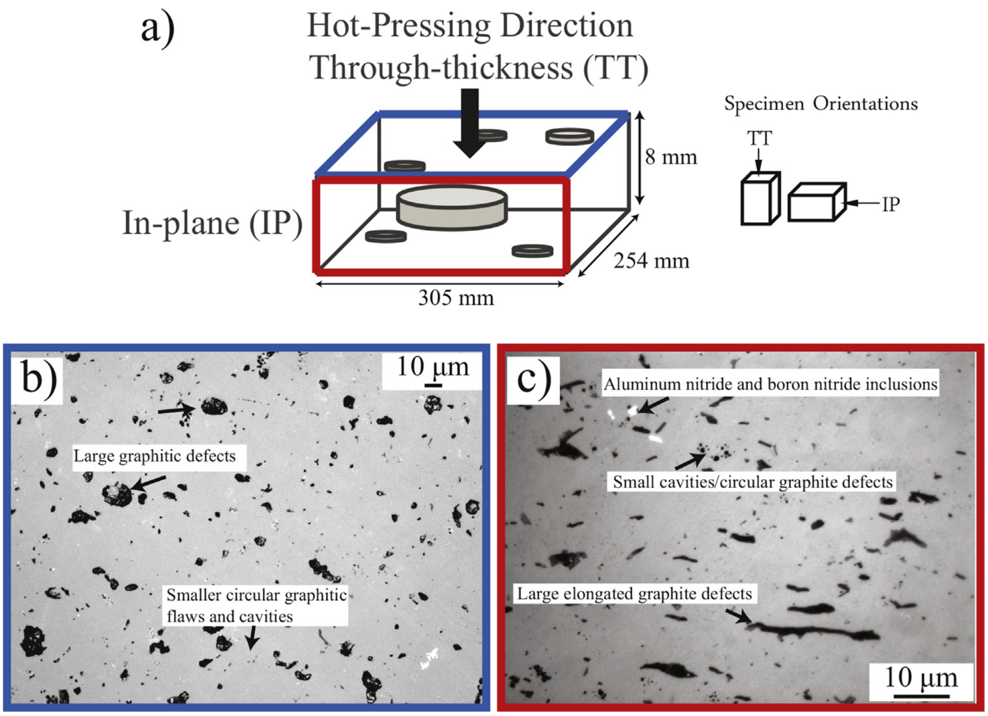

Fig. 1. (a) Conceptualized as-received tile of the hot-pressed boron carbide plate with through-thickness (TT) (in the hot-pressing direction) and in-plane directions (IP) labeled. Optical microscope images of the boron carbide microstructure in the (b) through-thickness (at 10× magnification) and (c) in-plane direction (100× magnification) with the various types of inclusions and defects.

Quasi-static uniaxial compression experiments were performed with an MTS servo-hydraulic test machine with a controlled displacement rate at a nominal strain rate of approximately 10^{-4} s^{-1}. The dynamic uniaxial compression tests were performed using a modified Kolsky bar apparatus. Kolsky bar testing has been previously used to study the dynamic behavior of a variety of ceramic materials [1,15–17], and experimental design is discussed therein. The nominal strain rates achieved in the dynamic tests were between 350 and 1000 s^{-1}. The incident and transmitted bars were 12.7 mm in diameter and made of maraging steel (VascoMax C-350) with a yield strength of 2.68 GPa, a Young's modulus of 200 GPa, a Poisson's ratio of 0.29 and a density of 8100 kg/m^3. Impedance-matched tungsten carbide platens were jacketed by Ti–6Al-4 V alloy sleeves, and were inserted between the sample and the bars to act as a buffer and protect against sample indentation. A small amount of high-vacuum grease was applied to the end faces of both platens and specimen to reduce friction resulting from the mismatched Poisson ratio. A Kirana high-speed video camera filming at 5 Mfps with a 500 ns exposure time was used to capture sample failure. A pulsed laser was used to illuminate the specimen surface. Output pulses from the camera were used to synchronize the camera images with the stress–time history recorded with the strain gauge on the transmitted bar.

2.1. *Microstructural characterization*

The inclusions and defects in the microstructure were characterized using a Zeiss optical microscope with an AxioCam MRC camera and a TESCAN MIRA3 field emission Scanning Electron Microscope (SEM) equipped with a fully automated electron backscatter diffraction (EBSD) analysis system and Energy Dispersive Spectroscopy (EDS) capabilities. The word “defect” is used to denote a microstructural feature that may serve as a failure initiation site (examined later) and “inclusion” to denote a feature that is not believed to contribute to failure (at least not under the stress-states studied here). The processing-induced inclusions and defects are most easily seen in optical microscope images such as those shown in Fig. 1b and c. The image on the left is taken on the