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Fragmentation of an advanced ceramic under ballistic impact: Mechanisms and microstructure

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ABSTRACT

In this paper, the impact-induced fragmentation of a commercially available hot-pressed boron carbide is explored. Fragmentation has been noted previously by many authors to be important in the impact performance of advanced ceramics, and so this paper seeks to provide some of the first near-complete and detailed measurements of individual fragment size and shape distributions available in the literature. Fragment size and shapes are quantified using methods developed in previous papers by the authors, and results reveal that two distinct fragmentation mechanisms exist as a consequence of the impact failure of boron carbide: one mechanism that creates small fragments that is associated with the coalescence of fractures originating from carbonaceous defects in the material, and one that creates larger fragments that is associated with structural failure (e.g., radial and circumferential cracking). While these mechanisms are similar to those noted for uniaxial compressive failure, results presented here highlight the importance of fragment shape as a consequence of impact failure. Namely, results indicate that both blocky and shard fragments are formed during impact into a boron carbide plate. Blocky and shard fragment types span across both the small and large fragmentation mechanisms. Using Scanning Electron Microscopy, blocky fragments were found to be associated with the predominant growth of cracks parallel to the impact direction, while shard fragments contain fracture surfaces that are associated with crack growth and coalescence in a direction perpendicular to the impact direction. The shards are, thus, believed to be a consequence of structural bending. No amorphous features were found on any blocky or shard fragments observed in this study (determined using Raman Spectroscopy), suggesting brittle fracture may be the dominant mechanisms that creates the shard fragments. Altogether, the implications of these results is that one can control fragment size and shape by controlling the carbonaceous defects population in boron carbide. This should help in the design of next-generation advanced ceramics for personal protection.

1. Introduction

The impact of a projectile into a target results in the activation of spatially and temporally evolving failure mechanisms originating from defects, including plasticity, phase transformations, and fracture. These mechanisms eventually manifest in fragmentation sizes, shapes, numbers and ejection velocities. The effects of fragmentation on the ballistic performance (resistance to penetration) of monolithic systems has been investigated by Krell and Strassburger [1], who noted that certain fragment size and shape can lead to better erosion of the projectile and energy dissipation. This has also been noted previously by, for example, Woodward et al. [2]. Other investigations involving the impact fragmentation of ceramics [3–5] have focused on studying the effect of material properties on performance. Krell and Strassburger [1] also discuss the links between performance and properties, and recognized that often both positive and negative correlations have been reported between performance and material properties such as strength, stiffness, and fracture toughness. The ambiguity of the results renders the design of ceramics quite challenging. Not often considered is the effect of microstructure on performance, with few studies performing detailed characterization on materials that are under investigation. In this study we build on these concepts as we attempt to link

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material properties and the microstructure with the impact fragmentation of a well-characterized hot-pressed boron carbide.

Boron carbide has received considerable attention in the literature as a suitable lightweight armour ceramic because of its high hardness and relatively low density in comparison to other advanced ceramics [3–6]. Boron carbide, however, has been shown to have an interesting impact response, in that: (1) the fragmentation behavior has been observed to change beyond 850 m/s [7], (2) the velocity of the damage wave has been shown to be constant before 650 m/s, after which it steadily increases [3], and (3) it has been observed to have no mescall zone [5]. Note that different projectiles, target geometry, levels of confinement, and materials were used across these and many experiments involving boron carbide. None-theless, they provide some guidance into the impact behavior of the material. For example, Transmission Electron Microscope analysis of the fragments from Moynihan et al. [7] by authors Chen et al. [6] revealed that the change in fragmentation may be related to the onset of a phase transformation, termed “amorphization”. Amorphization has also been reported to be associated with a decrease in impact performance, and since then, amorphization of boron carbide has received a considerable amount of attention in the literature [8–13].

In this paper, the impact fragmentation of boron carbide is studied for impact velocities of 275 and 930 m/s. These impact velocities are motivated by the interesting impact behavior previously described, where we seek to observe any transitional behavior in this material. In previous papers by the authors, the focus was on strength [14] and fragmentation [15] of the same hot-pressed boron carbide in uniaxial compression. In those papers, two fragmentation mechanisms were noted as a result of uniaxial compressive failure: one mechanism associated with the coalescence of fractures between carbonaceous defects, and one mechanism associated with structural failure. Using insights from those studies and new results involving silicon carbide, the authors developed a compressive brittle fragmentation model framework [16] that showed reasonable agreement with experimental measurements of compressive brittle fragmentation. In this current paper, this past work is expanded on by exploring the fragmentation mechanisms associated with impact of a spherical projectile into a styrofoam-confined boron carbide tile; noting the stress-state and strain-rates are more varied and complicated during impact than uniaxial compression. Impact-induced fragmentation processes have been widely noted in the literature to be important in ballistic performance [1,2,7,17,18], and so this paper seeks to use previous methods developed by the authors to provide some of the first near-complete distributions of individual fragment size and shapes in the literature. A similar framework for studying fragmentation is followed as presented in [15,16], but expanded for greater consideration for fragment shape. Shape consideration is motivated by Moynihan et al. [7], who noted a drastic increase in high-aspect-ratio “shard” fragments beyond a critical impact velocity of 850 m/s. In this paper, measurements of fragment size and shapes are used to inform about impact failure processes that are assessed through analysis of the failure surfaces using Scanning Electron Microscopy (SEM) and Raman Spectroscopy mapping. Key defects contributing to failure and fragmentation are identified in the microstructure, and then the spacing between these key defects are linked with fragmentation measurements. Finally, the experimental observations are discussed in the context of previously performed impact experiments by Sano et al. [19] on two boron carbide materials with different defect microstructures, with the objective of making links between microstructure, fragmentation, and impact performance.

2. Experimental setup

The impact experiments were conducted at the U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, USA. A 6.35 mm diameter spherical projectile made of 93% tungsten carbide, 6% cobalt, and 1% nickel was impacted at velocities of 275 m/s and 930 m/s (measured using flash x-ray) into targets that were 55 mm × 70 mm and 8 mm thick. The targets were made of a hot-pressed boron carbide (Coorstek, Inc.) with a Young’s modulus of 430 GPa and a density of 2510 kg/m^3. The material was received as plates, with the thickness direction of the plate parallel to the

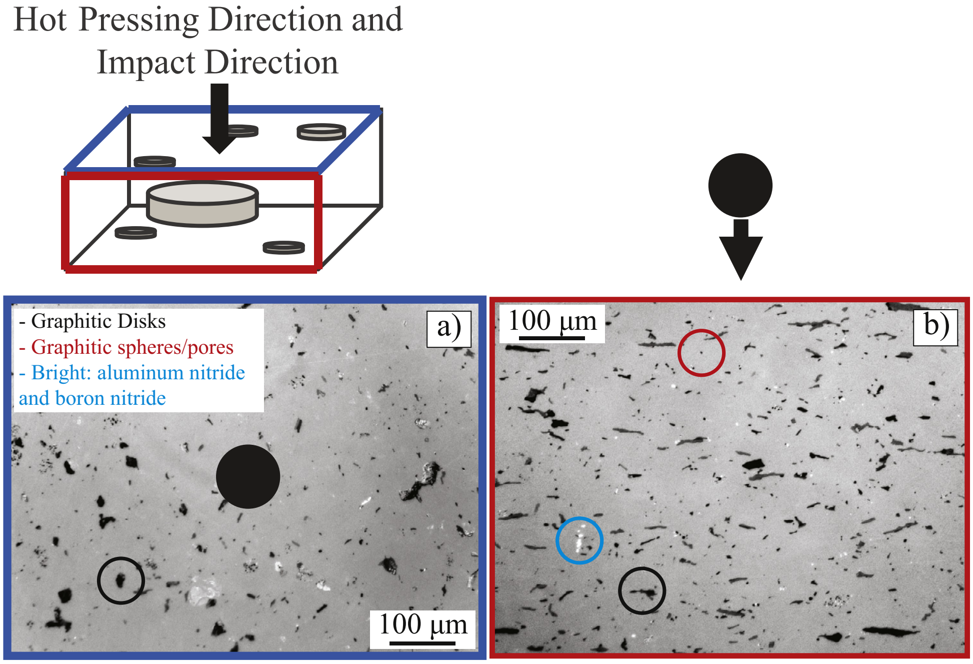

Fig. 1. (top left) Schematic of boron carbide tile with hot-pressing direction labeled and conceptual graphite disk defects. Optical microscope images of boron carbide microstructure for (a) through-thickness direction and (b) in-plane direction. Labeled in these images are microstructural features (defined in top left of image (a)) and the impact direction of the spherical projectile (the dark circular object).