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Dynamic deformation characteristics of zirconium diboride–silicon carbide under multi-axial confinement

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ABSTRACT

Multiaxial quasi-static and dynamic compression experiments were performed on zirconium diboride-5wt% silicon carbide (ZrB_2-5wt%SiC) ceramic composite processed via spark plasma sintering technique. Cylindrical ZrB_2–SiC specimens were confined using thick walled metal sleeves to generate various levels of confinement pressure on the lateral surface and then subjected to axial loads under quasi-static and dynamic conditions. Postmortem analysis revealed formation of a macroscopic shear plane in the recovered specimens and slip bands within ZrB_2 grains. Compressive strengths of up to 5.6 GPa and 9.8 GPa, respectively, were reached under quasi-static and dynamic strain rates. To capture the strain rate dependent and pressure dependent response the Johnson–Holmquist (JH-2) model was used and relevant parameters were determined for future high velocity impact or shock response simulations utilizing the experimental data generated from low and high strain rate confined compression tests. A comparison of JH-2 model constants for ZrB_2–SiC along with other structural ceramics revealed that pressure alone plays a deterministic role in defining the constitutive response of all brittle ceramics including ZrB_2–SiC.

1. Introduction

Ceramics exhibit brittle response [1,2], and in the presence of axial loading, exhibit catastrophic failure due to initiation of axial cracks from material inhomogeneities such as microvoids, microflaws and grain boundary glassy phases. The application of a lateral stress (confinement) delays or sometimes suppresses the activation and propagation of these tensile cracks, thus increasing the load-carrying capacity of the material. It has also been shown that application of large confinement stress can activate plastic flow or quasi-brittle behavior [2,3].

Confined compression experiments on brittle materials have been a subject of considerable interest since the earlier work of Bridgman [4]. Heard and Cline [5] observed a transition from brittle fracture to plastic flow under high radial confinement. Johnson et al. [6] investigated the deformation behavior of silicon carbide and pyroceram and reported strength enhancement at high strain rates, but a decrease in the strain rate strengthening with confinement. Lankford et al. [7] observed that at sufficiently high confinement pressures, strength data appeared to be independent of the test technique. Chen and Ravichandran [8,9] investigated the compressive peak strength sensitivity of AlN to both confining stress and strain rate and observed failure mode transition from axial splitting in the absence of confinement to shear faulting in the presence of confinement. Ahrens et al. [10], Chen and Ravichandran [11,12], Chocron et al. [13] and Ma and Ravichandar [14] investigated the effect of confinement pressure on ceramics and glasses and observed yield strength dependence on strain rate. Huang and Subhash [15] investigated the influence of lateral confinement on the dynamic damage evolution in brittle materials and found strong dependence of failure strength, damage accumulation and wing-crack growth rate on the nature and magnitude of confinement pressure. Luo et al. [16] used a double pulse Hopkinson bar technique to determine the response of the intact and damaged specimens. Paliwal and Ramesh [17] imposed bi-directional confinement on AlON samples and showed nonlinear stress evolution due to high planar confinement. Walker et al. [18] used an autofrettaged device and achieved confinement pressure as high as 1.0 GPa. Most recently, Shafiq and Subhash [19] used Raman spectroscopy and digital image correlation (DIC) to further verify the magnitude of confinement stress developed in SiC particles due to shrink fit assemblies. Summary of different confinement techniques was provided in a review article by Chen et al. [20].

In this manuscript, we will present the confined uniaxial compressive response of a ZrB_2–SiC ceramic composite and discuss its deformation behavior. ZrB_2–SiC is an ultra-high temperature ceramic (UHTC) and a potential candidate for advance aerospace structural components (e.g. nose cones, engine cowl inlets, shuttle belly skin tiles) designed for thermal shielding due to its ability to retain its intrinsic strength at elevated temperatures [21]. Hypersonic

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Table 1
Properties of ZrB_2–SiC composite.

Density [g/cm^3]	6.05 [19]
Melting point [°C]	~3200 [19]
Poisson's ratio	0.128 [19]
Elastic modulus [GPa]	517 [19]
Coefficient of thermal expansion [/°C]	6.74×10^{-6} [30]
Specific heat [J/kg.K]	493 @ 150°C [30]
Thermal conductivity [W/m.K]	90 [30]
Electrical conductivity [S/m]	10^7 [19]
Hardness [HV]	22 [19]
Fracture toughness [MPa√m]	2.6 [19]

vehicles designed for outer earth orbit or shuttles designed for interplanetary voyages require unconventional materials, which can withstand the extreme conditions of takeoff, landing and reentry to earth's atmosphere. Current aerospace materials are prone to thermal and chemical disintegration when exposed to severe thermal gradients (e.g. during atmospheric reentry) and extremely acidic environment, which pose greater risk to the carriers and crew members by either melting or oxidizing. ZrB_2–SiC, with its high melting point and excellent oxidation resistance, is considered as a promising solution to such problems. However, the material needs to be well characterized before it can be successfully incorporated into advance aerospace structural designs to warrant safe operation. While there is abundance of literature on the processing of ZrB_2–SiC, the design space remains widely unexplored due to the lack of in-depth knowledge on its deformation behavior. Recent indentation and scratch experiments [21–24] at room temperature have shown that ZrB_2–SiC ceramic can undergo limited plastic deformation even at room temperature. However, the distribution of stresses in these indentation tests is not uniform and the surrounding elastic material provides only limited confinement. On the other hand, confined compression tests provide an effective means to characterize ceramic materials under well-defined 3-dimensional stress state [8,9,11,12]. The confinement pressure can be quantified and related to the evolution of plastic deformation within the material. Recently, Ghosh et al. [22,24] have reported extensive dislocation based plastic deformation features in the form of slip lines during room-temperature indentation and scratch studies on polycrystalline zirconium diboride (ZrB_2) and zirconium diboride–silicon carbide (ZrB_2-5wt%SiC) composite. Despite having extremely high melting point (> 3000 °C) [25,26] and high hardness (22 HV) [27], the evolution of such macroscale dislocation features in ZrB_2 during room-temperature deformation is rather unusual and demands in-depth understanding of its constitutive response under a wide range of loading conditions to exploit its full potential in a variety of applications.

In this manuscript, the results of an investigation of deformation mechanisms of ZrB_2–SiC as a function of applied confinement pressure and strain rate are presented. The fractured ceramic assemblies were recovered and analyzed using SEM. The Johnson-Holmquist (JH-2) model parameters were determined for ZrB_2–SiC by utilizing experimental results from quasi-static and dynamic compression experiments [28,29].

2. Experimental

2.1. Material and specimen preparation

A ZrB_2-5wt%SiC ceramic composite processed through spark plasma sintering (SPS) technique was used in this study [23]. Table 1 lists some salient properties of this composite available in the published literature. The sintered composite contained two crystalline phases, namely hexagonal (H) ZrB_2 matrix and cubic (3C) SiC particles with an average grain size of 5 µm and 1 µm, respectively [24]. The unusual high electrical conductivity of ZrB_2–SiC (~10^7 S/m) [22] ceramic allowed for electric discharge machining (EDM) of cylindrical specimens of 4 mm diameter and 8 mm in length out of a billet as shown in Fig. 1a. The specimens were polished using standard metallographic techniques to remove any EDM induced surface damage.

2.2. Dilatational constraints

To investigate the role of confining pressure on the deformation behavior of ZrB_2–SiC ceramic, four different confinement pressures were imposed on the lateral surface of the specimens using hollow metallic sleeves made from different materials as shown in Fig. 1b. Aluminum (Al), copper (Cu), brass (brass) and stainless steel

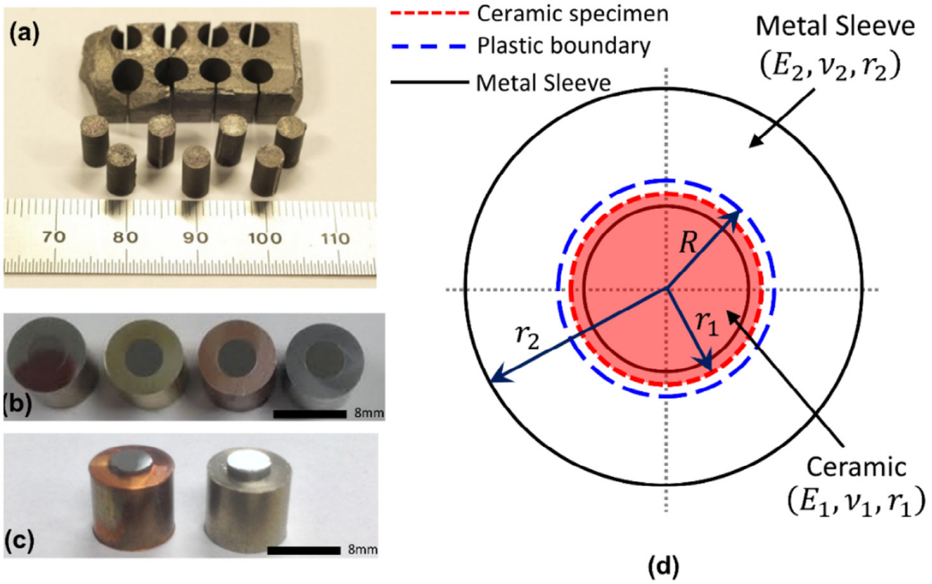

Fig. 1. (a) Cylindrical specimens of ZrB_2–SiC machined using EDM, (b) shrink-fit specimen assembly with various metal sleeves, (c) un-flushed ceramic-sleeve assembly to assess the contribution of sleeve material on dynamic stress-strain behavior under confinement, and (d) schematic of an axisymmetric boundary value problem of an elastic ceramic specimen and elastic-perfectly plastic hollow cylindrical metal sleeve.