Available online at www.sciencedirect.com

ScienceDirect

Journal of the European Ceramic Society 35 (2015) 197–210

www.elsevier.com/locate/jeurceramsoc

Wave propagation through alumina-porous alumina laminates

Pathikumar Sellappan [a], Erheng Wang [b], Christian J. Espinoza Santos [a], Tommy On [b], John Lambros [b], Waltraud M. Kriven [a,*]

[a] *Department of Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA*
[b] *Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA*

Received 6 May 2014; received in revised form 25 July 2014; accepted 9 August 2014
Available online 30 August 2014

Abstract

A Brazilian disk geometry of an alumina layered composite with alternating dense and porous layers was dynamically loaded using a Split-Hopkinson Pressure Bar (SHPB) apparatus under compression. High-speed imaging and transmitted force measurements were used to gain an insight into stress wave propagation and mitigation through such a layered system. Uniformly distributed porosities of 20 and 50 vol% were introduced into the interlayers by the addition of fine graphite particles which volatilized during heat treatment. Brazilian disk samples were cut from the cylinders which were drilled out of the sintered laminated sample. The disks were subjected to dynamic impact loading in perpendicular and parallel orientations to the layers in order to investigate the influence of the direction of impact. The dynamic failure process of the layered ceramic consisted of the initiation and propagation of the cracks mainly along the interphases of the layers. Upon impact, the impact energy was dissipated through fracture in parallel orientation (0°) but transmitted in perpendicular (90°) orientations. The high degree of correlation between the transmitted force, microstructure and orientation in which the layered systems were impacted is discussed.

Keywords: Alumina/porous alumina laminates; Porous ceramics; SHPB; Dynamic impact; Stress-wave mitigation

1. Introduction

Even though ceramics exhibit unpredictable failure, various components in the form of monolithic tiles, coatings and fibers have been extensively employed in structural applications, especially as armor materials[1–3]. Due to their attractive mechanical strength properties, both oxide (mainly alumina and zirconia-based)[4]and non-oxide (carbide, nitride, boride, etc.)[5–8] based structural ceramics have attracted considerable attention for use under impact loading. In armor usage, when a hard projectile impacts a ceramic object, the impact area might be fractured, pulverized, and/or ejected, depending on the dynamic impact conditions.[1,9] Fracture as well as fragmentation of the impact plates are effective ways to dissipate the impact energy which consequently protects the backing surface.[1] The extension of time of impact and redistribution of the impact load over a wider area on the supportive backing structure helps to reduce the stress concentration during the dynamic failure process.[1] The ability to guide and deflect cracks enhances the energy dissipation and this can be achieved using interphases that are weaker than stiff plate materials.[2,9] Furthermore, the complex dynamic compressive behavior of brittle solids such as ceramics, rocks and concretes has been studied extensively using a Split Hopkinson Pressure Bar (SHPB) arrangement.[3,10,11] The SHPB, which was originally developed by Kolsky,[12] has been modified to determine the dynamic deformation behavior of materials under controlled strain rates ($10^2\ s^{-1}$–$10^4\ s^{-1}$). In reality, such extreme loading conditions are indeed changing the way that brittle materials usually fail on an atomic scale.[13]

There are several research efforts that have been made to understand the role of different parameters (strain rate, microstructure and environmental effect, etc.) on the fracture and failure of ceramics under dynamic loading. However, in comparison with our understanding of the microstructure-property relation under static loading, the dynamic mechanical response of structural ceramics is still a young and topical

* Corresponding author. Tel.: +1 217 333 5258; fax: +1 217 333 2736.
E-mail address: kriven@illinois.edu (W.M. Kriven).

http://dx.doi.org/10.1016/j.jeurceramsoc.2014.08.013

engineering problem. Simultaneously possessing all the basic requirements such as low density, high strength and high toughness to design better ballistic protection is not possible using the available engineering materials alone. Therefore, concepts of layered structures have been successfully implemented for armor applications.[9,14,15] Ceramic layered systems have attracted wide attention due to the crack deflection capability in the weak interlayers which has been shown to be effective in improving toughness of components.[16–20] In these layered ceramic systems, toughness improvement is the result of crack deflection which mainly depends on the fracture energy absorbed in the interphase of the laminates.[20] Current literature on the high-strain rate deformation behavior of laminated systems is either limited to biological and metallic systems or compressive stress-strain analyses in the case of ceramic laminates.[21–23] However, layered structures of such brittle constituents are not only present in man-made materials but also in naturally available materials like bone, nacre and the conch shell.[24,25] Understanding the deformation behavior of naturally available, brittle layered systems can help us to design better armor components.[24,26] For example, in biological systems such as *Nacre* and *Strombus gigas*, mechanical behavior depends on the orientation in which a sample was tested, due to their complex layered microstructures.[25] In the past, some attempts have been made to mimic naturally available systems to process layered ceramics at the microstructural scale,[26,27] but testing under various orientations, and under dynamic loading has not been performed until now, in part due to severe difficulties associated with fabrication of appropriate bulk samples.

Investigating stress-wave mitigation in layered systems based on the orientation, strain rate, varying the weaker layer thickness ratio, and density can help to design better materials for ballistic protection.[1] Determining constitutive and failure models of dynamic impact studies will help to develop numerical simulations which will give critical information on armor performance.[14,28,29] In order to obtain reliable and reproducible predictive models, materials data under high-strain rate or high pressure or a combination of both are highly desired.

In the present study, we successfully implemented key processing features to fabricate a model system, in the shape of a Brazilian disk, consisting only of alumina, with alternative dense (stronger) and porous (weaker) layers in its microstructure. Our approach was not only selected to investigate the stress-wave mitigation behavior in a specific and desired direction in a controlled way, but also to visualize the dynamic failure and fracture processes easily. The alumina/porous alumina combination was chosen based on previous studies on the importance of a chemically compatible interphase so as to avoid the accumulation of internal residual stresses.[30–32] The best way to achieve such a system is to fabricate laminates with porous interlayers of a material of composition which is the same as that of the dense material.[20,30] In this study, we used fine graphite particles as pore formers to introduce uniformly distributed, fine, architectured porosity into the porous interlayers. Furthermore, the present investigation focuses on the dynamic force response with respect to the orientation of the layers, rather than on the compressive stress-strain behavior. A modified SHPB apparatus with a momentum trap was employed to investigate wave propagation and the load transmission results are discussed in correlation with high-speed imaging results.

2. Experimental procedure

2.1. Laminate fabrication

Dense and porous alumina green tapes were produced using commercially available alumina (A16SG, Almatis, Leetsdale, PA, USA) and graphite powders (Aldrich Chemical Company, St. Louis, MO, USA) as precursor materials. The fine alumina powders were 99.8% chemically pure with an average particle size of (D_{50}) 0.45 μm and a surface area of 8.5 m^2/g, and had a density of 3.98 ± 0.01 g/cm^3. Graphite particles with appropriate amounts of 0, 20, and 50 vol%, were introduced into the slurry which contained A16SG alumina particles. The graphite particles used as pore formers had a 1–2 μm particle size and a 1.9 g/cm^3 density. A formulation supplied by Polymer Innovation, Inc® (Vista, California, USA) was used to prepare the slurries and it contained (i) acrylic binder (WB4101) which consisted of defoamer, plasticizer, and resin to produce basic tapes, (ii) a non-silicone mild defoamer (DF002), and (iii) a high pH plasticizer (Pl002). This polymer was a combination of strong dispersing molecules and partly strong binder molecules to help in milling the slurry without excessive foam or destabilization.

Powders, de-ionized water and appropriate amounts of binder were added at the first stage to obtain very low viscosity slurries which later resulted in a stable suspension. The slurry compositions used to prepare both graphite-containing and graphite-free tapes are given in Table 1. The ingredients were mixed by ball milling (at 92 rpm for 16 h) using yttria stabilized zirconia cylinders as milling media. The remaining ingredients were then added and ball milling was continued for 4 more hours. After milling, the resulting slurries were drained and sieved through a mesh, followed by de-airing using a vacuum desiccator and left in a fume-hood for 5 min to remove any existing air bubbles. The slurries were then tape cast on to Mylar sheets using a hand-held doctor blade having an initial thickness setting of 250 μm, which was then reduced to ∼125 μm thickness after drying in air.

After drying, the tapes were cut into 38 mm squares, stacked, and pressed together in a custom designed die at 72 °C, under a pressure of 10 MPa for 10 min. The pressure was increased to 20 MPa and held for 20 min to fabricate samples of ∼37 mm thickness, as shown in Fig. 1(a). To investigate the role of porous layers under dynamic impact, samples were made by alternatively stacking graphite-free (dense alumina) and graphite-containing (porous alumina) tapes. In all the cases, 5:1 ratios of dense alumina to porous alumina layers (20 and 50 vol%) were maintained. For comparison, monolithic dense alumina was also fabricated using the same technique but without graphite addition. These are hereafter referred to as dense alumina, 20 vol% and 50 vol%, respectively. Binder and graphite burnout were carried out based on thermogravimetric analysis (TGA, Netzsch STA 409 CD, Selb, Germany)