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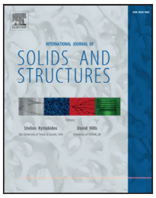

Controllable fracture in shocked ceramics: Shielding one region from severely fractured state with the sacrifice of another region

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ABSTRACT

Pre-existing defects in ceramics induce shock-wave compression fractures and may lead to the failure of designed functions. Instead of sintering fully dense ceramics, which is difficult to implement and ineffective under shock, we propose a novel strategy for fracture modulation by deliberately adding more pores into the ceramics. This approach may seem counterintuitive, but it has been shown numerically and experimentally that a "shielded region", which is free of severe shock fracture, can be formed with the sacrifice of a "damaged region" in the porous ceramics. The damage evolution and the shock response of porous ceramics were simulated with a lattice–spring model. The mechanism is interpreted from the relationship between the collapse of mesoscopic voids and the evolution of the macroscopic shock wave. Shock and soft-recovery experiments were conducted and the results confirmed the existence of the shielded region. It was found that, under shock conditions, where a dense sample was damaged, all the voids in a porous sample close to the impact surface had collapsed; however, in the other half of the sample, numerous intact voids still remained. This new concept provides guidance for the avoidance or delay of shock failure in functional ceramics.

1. Introduction

Shock-wave compression fracture is a common phenomenon observed in brittle materials and is important not only to dynamic fracture, but also to the origin of shock failure of structural and functional ceramics (Kanel et al., 2009; Grady, 1998; Bourne et al., 1998; Graham, 1979). A shock wave is a powerful amplifier of defects in that it activates pre-existing defects (e.g., micro-voids, cracks and grain boundaries), extends cracks, and breaks media. Mechanical, electrical, and optical properties of ceramics are severely affected by shock waves (Bourne and Millett, 2007; Zhang et al., 2013; Hao et al., 2007), and consequently it may not be possible to realize the designed functions of shocked ceramics, such as in the cases of high-strength ceramics for armor (Lankford et al., 1998), piezoelectric and ferroelectric ceramics for converting mechanical energy to electrical energy (Jiang et al., 2012; Graham and Ingram, 1972), and transparent ceramics for optical measurements in shock experiments (Li et al., 2008). One traditional strategy for failure prevention has been by sintering "defect-free" ceramics (e.g., a large, perfect single-crystal sample). However, such treatment by sintering is difficult in practice and costly in expense, and more importantly, it only increases the critical emergence stress of shock fracture rather more than eliminating the probability of shock failure. Adopting an approach that is the opposite of creating defect-free ceramics, we may be able to control shock fracture and avoid the shock failure of ceramics by properly introducing defects.

The control of shock fracture by introducing defects may seem counterintuitive. However, under quasi-static loading, there have already been many successful cases in which defects were introduced to avoid catastrophic fracture, showing that defects do not always result in uncontrollable fracture. In nature, highly mineralized natural materials owe their exceptional toughness and quasi-ductility to microscopic building blocks, weak interfaces and architecture (Yahyazadehfar et al., 2013; Barthelat and Rabiei, 2011; Barthelat et al., 2007). In engineering, the fracture toughness of "hard and brittle" glass and metal glasses has been increased

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by properly introducing micro-cracks and voids (Mirkhalaf et al., 2014; Sarac and Schroers, 2013; Qu et al., 2012). These mechanisms can be summarized as crack shielding, deflection, and bridging, which effectively reduce the crack-driving force (Launey and Ritchie, 2009). In shock applications, however, the difference is that a shock wave relates to a high-power pulse. The stress and the energy input are sufficient to vanquish various toughening strategies. Hence, numerous cracks nucleate and grow inevitably. In this case, strategies for toughening brittle materials cannot be duplicated. Instead, we proposed a novel approach in addressing shock fracture, i.e. by introducing defects to modulate and tailor the propagation of crack network in shocked ceramics.

Valuable insights into mechanisms of shock-wave compression fracture of brittle materials have been obtained by taking experimental and numerical approaches. Defects, such as voids and cracks, induce severe shear stress concentration when a shock wave sweeps through a medium; if the shear stress around the defects exceeds the strength of the medium, cracks nucleate and grow (Grady, 1998; Yu et al., 2014). Mesoscale evolutions of crack network induced by pores, micro-cracks and glass pocket inside ceramics were simulated by Espinosa and co-workers (Espinosa and Zavattieri, 2003a, 2003b; Zavattieri et al., 2001). Macroscopic wave profiles of polycrystalline alumina were measured and calculated by Bourne and Millett (2007) and Chen et al. (2006). However, few efforts have been made to modulate shock fracture. This is due to the absence or uncertainty of correlation between the micro/mesoscale damage process and the evolution of the macroscale shock wave. While this correlation is difficult to obtain in shock experiments or in employing any one of many numerical methods, a lattice–spring model (LSM, also known as discrete element method) that we built provides the evolutions on both scales and their correlation (Yu et al., 2014). It allows us to explore a new strategy to control shock fracture and identify its mechanism.

A void is a defect that can be most easily introduced into ceramics with high precision (porosity, void diameter and void shape can be controlled accurately (Zeng et al., 2007)). In this work, we explore the mechanism and process of damage evolution in shocked porous ceramics, and report that micro-voids can be used to control the fractured region. We have shown both numerically and experimentally that by deliberately adding pores into the ceramics, a "shielded region" that is free of shock fracture can be acquired with the sacrifice of a “damaged region”.

2. Computational and experimental details

2.1. Model for shocked ceramics

Shock fracture of a ceramic corresponds to evolution of a crack network following the shock wave. Although some excellent work has been conducted on modeling ceramic shock fracture via mesh based computational methods (Bourne and Millett, 2007; Espinosa and Zavattieri, 2003a, 2003b; Zavattieri et al., 2001; Chen and Ghosh, 2012), it is believed that mesh-based methods encounter significant challenges when dealing with fracture and fragmentation induced by shock wave compression. The reason is that partial derivatives are used in mesh-based methods to represent the relative displacement and force between any two neighboring particles (Silling, 2000). But the necessary partial derivatives with respect to the spatial coordinates are undefined along the cracks and need to be redefined. However, the redefinition requires us to know where the discontinuity is located. This limits the usefulness of these techniques in addressing problems involving the spontaneous formation of cracks, in which we might not know their location in advance (Silling, 2000). In contrast, particle methods (e.g., Peridynamics: Silling, 2000; Silling et al., 2007; Ha and Bobaru, 2010; Ghajari et al., 2014; Demmie and Ostoja-Starzewski, 2016) and LSM: Zhao et al., 2011; Wang and Mora, 2008; Buxton et al., 2001)), which have been developed extensively in recent years, can avoid various numerical difficulties caused by displacement discontinuity.

The peridynamics has become well known for its ability to grasp spatial discontinuities without ambiguous interpretations of spatial derivatives (Demmie and Ostoja-Starzewski, 2016). The bond-based (Silling, 2000), state-based (Silling et al., 2007), and stochastic peridynamic (Demmie and Ostoja-Starzewski, 2016) theories have been developed to provide a consistent treatment of deformation and failure of a medium with an alternative formulation of continuum mechanics. The LSMs are frequently used to simulate deformation and fracture of both homogeneous and heterogeneous solids. They originate in the atomic lattice models of elasticity and lattice dynamics of crystals and, from this perspective, they can be viewed as continuum level counterparts of the atomic lattice models. The essence of these methods is that integration, rather than differentiation, is used to compute the force on a material particle. Since the spatial derivatives are not used, the equations remain equally valid at surfaces of discontinuity.

In the LSM, continuum medium is described as discrete material particles (which are composed of numerous atoms) (Steinhauser et al., 2009). The nearest neighboring particles are interconnected and interact through springs. Evolution of this network can represent correctly the global response of macroscopic materials, if the interactions of material particles are described accurately. Through simplifications of real materials, and the model’s discrete nature, LSM has the advantage in treating fracture, fragmentation, and other dynamic damage processes of brittle materials subjected to tension, compression, shear and other complex loading (Yu et al., 2014).

A two-dimensional (2D) LSM was used in this work. It was set as elastic–brittle response, which ignores the small plasticity contribution to the response that may exist in ceramics. Stress relaxation was not added to the springs; however, macroscopic plasticity and relaxation may still emerge, if deformations occur on a spatial level higher than the lattice and spring network. Between pairs of nearest-neighbor particles, linear elastic interaction is used in a pair of springs before fracture: a normal spring exists that provides central potential forces and a tangential spring that provides shear resistance forces. If only the normal springs are considered, such a model (so-called “Hookean model”) only has a fixed Poisson’s ratio. However, if the tangential springs are included, the model (so-called “Born model”) can represent materials with different Poisson’s ratio (Buxton et al., 2001). A rotational degree of freedom for particles is introduced in our model to restore automatically the rotational invariance of the model, which is absent in most Born models (Yu et al., 2014). To describe the fracture process, a fracture criterion based on Griffith’s energy balance principle is employed. When one particle has a displacement relative to another, the sum of the tension deformation energy in the normal spring and shear deformation energy in the tangential spring is calculated. If the summation exceeds a certain threshold corresponding to the energy of forming a micro-crack between the two particles, the two springs break irreversibly. Between broken particles, there are only repulsion and friction interactions (Yu et al., 2014).

The parameters used in the interaction formulae of LSM were usually given empirically, resulting in a qualitative representation of mechanical properties of target materials. Several outstanding studies have been done to overcome this shortcoming (Zhao et al., 2011; Case and Horie, 2007; Yano and Horie, 1999; Ostoja-Starzewski, 2002; Grah et al., 1996; Wang et al., 2000). Gusev proposed a parameter mapping procedure between finite-element method (FEM) and LSM (Gusev, 2004): consider a network that is both a LSM lattice and a FEM mesh; first, elastic constants of the target material are transformed into stiffness matrix