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ScienceDirect
Ceramics International 41 (2015) 12763–12772
CERAMICS INTERNATIONAL
www.elsevier.com/locate/ceramint

Dynamic failure and fracture mechanism in alumina ceramics: Experimental observations and finite element modelling

Zhiyong Wang, Peifeng Li*

School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Received 9 April 2015; received in revised form 27 May 2015; accepted 25 June 2015
Available online 2 July 2015

Abstract

The application of ceramics in composite armour requires the investigation on the failure and fracture mechanisms of the ceramics under dynamic loading. In this study, the split-Hopkinson pressure bar technique with high speed photography was used to directly observe the dynamic macro-cracking and fragmentation process in alumina and to characterise the stress and strain histories. An experimentally validated 3D finite element model of the full scale test was developed to predict the stress distribution and damage evolution in alumina that were related to the experimental observations. It was found that the damage (cracking) evolution is determined by the multiaxial stress state, in particular the substantial localised tensile stress concentration and the stress direction. The cracking process leads to the longitudinal axial splitting failure on the surface and the internal diagonal damage bands. The dynamic failure process in alumina is dominated by both the intergranular and transgranular fracture mechanisms.
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Keywords: Ceramics; Dynamic behaviour; Failure; Finite element model; Strain rate

1. Introduction

Composite armour composed of material layers such as ceramics, metals and adhesives has received tremendous interests due to the light weight, good shock resistance and excellent impact energy dissipation capacity [1–5]. The ballistic performance of composite armour is strongly dependent upon the dynamic behaviour of its layered materials, in particular the ceramics in which the strength increases with the confining pressure [3,6]. However, unlike metallic layered materials such as steel and aluminium alloys [7,8], the properties of ceramics subjected to dynamic loads are not well characterised and understood due to the high failure strength and low failure strain [1,4]. Moreover, ceramics tend to be sensitive to the strain rate especially when it is above a critical value [4,9]. To enable the use of ceramics in composite armour structures, it is necessary to investigate the dynamic deformation, failure and fracture mechanisms of the ceramics.

A portion of research has been conducted to study the failure mechanism of ceramics in the two length scales: (1) the nucleation, growth and interaction of micro-cracks, and (2) the macroscopic failure behaviour including macro-cracking and fragmentation [10–15]. Micro-cracks nucleate at heterogeneities in ceramics such as grain boundaries and inclusions [13]. Microstructural features have a significant effect on the micro-crack propagation path; and micro-cracking plays a crucial role in determining the overall failure behaviour in ceramics [14–18]. The fracture of grains (i.e., transgranular fracture) and the failure of grain boundaries (i.e., intergranular fracture) can be the possible fracture modes in ceramics dependent on the chemical compositions, microstructure and the external loading rates. Experimental observations in various length scales have exhibited that the failure and fracture process in ceramics is significantly influenced by the loading rate. Although the simplex failure mechanism in ceramics has been observed under quasi-static rates [19], the appearance of dislocation at the tip of micro-cracks causes different complex

*Corresponding author. Tel.: +65 6790 4766.
E-mail address: peifeng.li@ntu.edu.sg (P. Li).

http://dx.doi.org/10.1016/j.ceramint.2015.06.110
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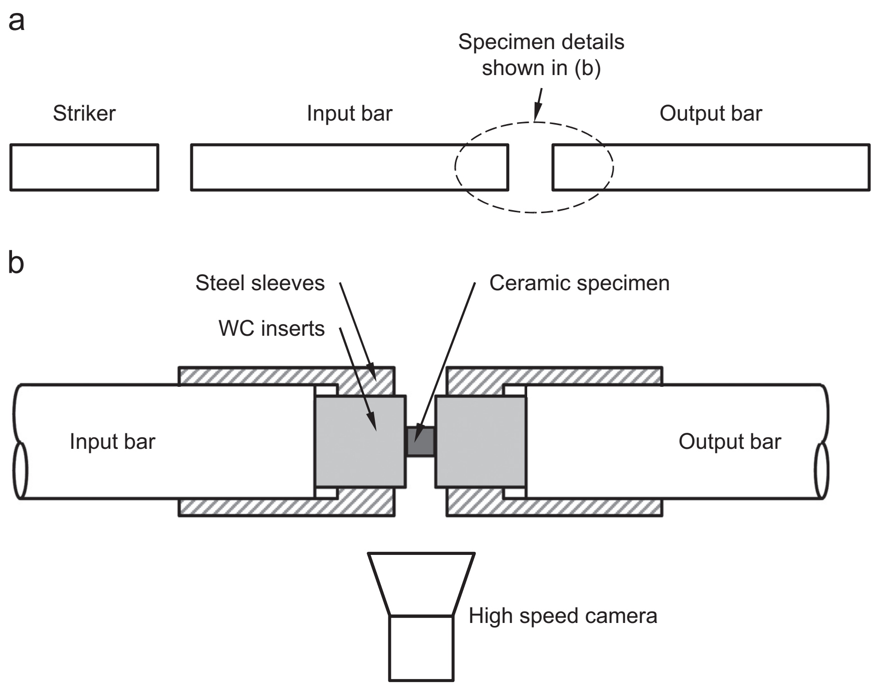

Fig. 1. (a) The schematic of the split-Hopkinson pressure bar (SHPB) system and (b) the setup of the ceramic specimen and high speed camera.

failure processes in the ceramics under dynamic loading. It is important to directly explore the underlying mechanism for dynamic failure and fracture process in ceramics.

A number of existing experimental studies have focused on the macro-cracking process and fragmentation during the failure of various ceramics subjected to dynamic loading [5,9,20]. It can be argued that the complex dynamic failure and fracture mechanisms may vary from one ceramic material to another, which are intrinsically determined by the chemical compositions and microstructural features arising in the manufacture (e.g., sintering or hot-pressing). For a specific ceramic, characterisation of the dynamic behaviour is thus required for its application in composite armour.

Numerical simulation such as finite element (FE) modelling has been extensively used to predict the stress distribution in ceramics subjected to dynamic loads and investigate the damage evolution that it is usually difficult to observe experimentally due to the instantaneous nature at high rates. For accurate numerical simulation, various constitutive models have been developed to quantify the mechanical response of ceramics under different loading rates. Taylor et al. [21] assumed that the damage in brittle rocks only accumulates in a tensile state and then proposed an ideal plastic constitutive equation to simulate the dynamic fracture behaviour of the rocks. A mixed-mode cohesive law to describe the fracture process was implemented in a FE model to predict the dynamic fracture and fragmentation of various ceramics [22]. The Johnson–Holmquist material model with damage (JH-2) [3,23] incorporates the polynomial equation of pressure state as a function of volumetric strains, the specific strength for both the intact and fractured materials, and the damage evolution rule to determine the occurrence of fracture in ceramics. The JH-2 model has been widely accepted to simulate the mechanical behaviour of damaged brittle materials subjected to high pressures, large strain and high strain rates.

The aim of this study was to investigate the mechanism of the failure and fracture behaviour of alumina subjected to dynamic loads. Dynamic uniaxial compression experiments in a split-Hopkinson pressure bar (SHPB) system fitted with high speed photography were conducted to quantify the stress history of alumina and directly observe the failure process in real time. The fracture surface on alumina fragments was examined in scanning electron microscope (SEM) to further explore the fracture mechanism in the failure process. An experimentally validated FE model consisting of the full scale SHPB bars and the alumina specimen was developed to simulate the stress distribution and the damage evolution in alumina. The FE predictions were combined with high speed photographic observations to analyse and determine the dynamic failure mechanism in alumina.

2. Experimental procedure

Cylindrical alumina specimens (Chair Man Hi-Tech Co. Ltd., Taiwan) of the diameter d=5 mm and the length l=5 and 12 mm were manufactured for uniaxial compression experiments at dynamic and quasi-static strain rates, respectively. The end surfaces of the specimens were polished to produce good perpendicularity from the longitudinal axis. As surface defects may lead to early failure of ceramics during compression, the specimen surfaces were examined in optical microscope prior to mechanical testing, and only the specimens without surface defects were tested. The specimen ends were lubricated with Castrol LMX grease to minimise the interfacial friction that may induce complex stress states in the specimen under uniaxial compression.

The dynamic uniaxial compression experiments of alumina specimens (d=5 mm and l=5 mm) were conducted in a split-Hopkinson pressure bar system schematically shown in Fig. 1(a).

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