Journal of Asian Ceramic Societies 4 (2016) 324–328

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Journal of Asian Ceramic Societies

journal homepage: www.elsevier.com/locate/jascer

Competition between random and correlated accumulation of primary damages in impact-loaded SiC ceramics

Alexandre Chmel*, Andrej Kadomtsev, Igor' Shcherbakov

Ioffe Institute, 26 Polytechnicheskaya, St. Petersburg 194021, Russia

ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form 4 May 2016
Accepted 10 June 2016
Available online 27 June 2016

Keywords:
SiC ceramics
Impact loading
Fractoluminescence
Time series

ABSTRACT

Samples of SiC ceramics differing in porosity in the range 1–9% were damaged by a falling weight, and the fractoluminescence (FL) activity lasting up to 0.4 ms was detected with the time resolution of 10 ns. The recorded time series of the light emission were used for constructing the distributions of the energy release in FL pulses and the time intervals between pulses. The energy release in damage events evolved from a self-similar (power law) distribution in low porous ceramics to a fully random (exponential) distribution in more porous samples. The sequence of time intervals between FL pulses exhibited an opposite trend as transforming from the fully random set of "waiting times" in lower porous ceramics into the self-similar time distribution in the most porous ceramics. These changes in the mechanical behavior of tested ceramics were explained by the formation of the oxidized film on the pore surface and by the increasing structural role of bridges between sintered particles in more porous ceramics, which serve as stress concentrators.

1. Introduction

The important feature of macroscopic damage/fault formation is the cumulative effect of primary defect nucleation, which manifests itself both in quasi-static and impact loading of heterogeneous materials [1]. The fracture process in the presence of multiple newly formed defects exhibits a trend to cooperative behavior owing to the defects interactions. The dynamic connectedness of the ensemble of defects is performed through elastic waves propagating from local failures. Long-range interactions (if ever exist) lead to the scaling invariance of space, time, and energy parameters of the multiplicity of microcracks in a loaded/strained body under specific conditions [2–4]. However, various structural and temporal restrictions could affect to any extent the degree of interactions up to full disappearance of the cooperative phenomena, which reflect indirectly the conditions of the damage nucleation in loaded solids.

In this work, we present experimental data on the impact damage of silicon carbide (SiC) ceramics differing in their physical and mechanical properties. The silicon carbide (SiC) and SiC/SiC composites are used in many industry applications [5], including rocket engine components [6] and both civilian and military armor equipment [7,8]. These applications are based on high strength and impact resistance of various forms of SiC; however, their use as engineering materials is limited by brittleness and liability to catastrophic failure [9]. Therefore, the mechanism of the damage initiation in connection with the elastic/ductile properties of SiC ceramics is of interest from the viewpoint of achieving their highest performance.

The samples of SiC ceramics differing in their pore concentration were damaged by a falling weight, and the time series of light pulses induced by the fractoluminescence (FL) effect [10] were recorded and processed. The FL originates from the reconfigured electronic structure in broken bonds; therefore, the light emission gives information on the damage process occurring at the nanostructural scale level.

The FL amplitude determined by the total energy of detected photons is proportional to the energy release in primary damage events. The time intervals ("waiting times") between pulses characterize the temporal coherence of the damage initiation and accumulation. The data processing of the time series showed that in dependence of the physical and mechanical characteristics of tested ceramics, the scale invariance took place either in the amplitude distributions or in the distributions of time intervals; in addition, the uncorrelated, fully random distributions of both energy and temporal parameters were detected in some specific cases.

* Corresponding author.
E-mail address: chmel@mail.ioffe.ru (A. Chmel).

Peer review under responsibility of The Ceramic Society of Japan and the Korean Ceramic Society.

http://dx.doi.org/10.1016/j.jascer.2016.06.001
2187-0764

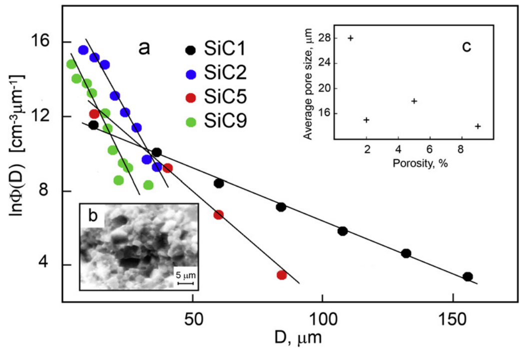

Fig. 1. Differential distributions of pore size in tested samples (a); SEM microphotograph of a typical pore in material (b); average pore size (diameter) in dependence of sample porosity (c). Straight lines fit Eq. (1).

2. Samples and equipment

2.1. Porosity

Porous SiC ceramics were prepared by sintering the silicon carbide particles of ~0.2 in size. At elevated temperatures, the particles sintered in grains of 2–6 µm in diameter. By changing the content of additives Al_2O_3, Y_2O_3, B, and C and varying sintering temperature in the range 1920–2250 °C, a set of ceramic samples with porosity (P) of 1%, 2%, 5%, and 9% (denoted hereafter SiC1, SiC2, SiC5, and SiC9, respectively) was prepared.

Plates of ~2 mm thick were cut from the original samples; their faces were ground and polished with a set of diamond powders with a final size of 1 µm. The microphotographs obtained with an optical microscope were used for estimating some quantitative characteristics of the porous materials. Fig. 1a shows the differential distributions of pore size in tested samples, $\Phi(D) = \Delta N(D)/\Delta D$, where $\Delta N(D)$ is the amount of pores of size D in the interval $D \pm \Delta D$ that referred to a unit volume of ceramics, which was calculated from the processing of the microphotographs. The calculations were carried out on the assumption of the spherical form of pores; a SEM microphotograph of a typical pore in the material (Fig. 1b) justifies such an assumption as satisfactory. The average pore sizes in the samples in dependence of porosity are shown in Fig. 1c.

The differential distributions are plotted in semi-logarithmic coordinates. The experimental points that fall upon straight lines corresponded to the exponential law:

$$\Phi = A\exp(-\delta D) \quad (1)$$

where A is the constant and δ is the slope of line. The exponential (Poisson-like) law describes a random distribution of specific objects, i.e. pores in our case.

2.2. Loading

A surface damage was produced by a hard pointed striker established on the upper face of the sample, on which a 100 g weight was dropped. The surface damages on the tested samples are depicted in Fig. 2.

The data acquisition system was triggered in the moment of the FL beginning. Light emission was collected with a quartz lens and directed onto a photomultiplier FEU136. An analogue-to-digital converter ASK-3106 provided the dynamic range 2 mV to 10 V (70 dB) in the time range 10 ns to 100 s. The converted (digital) FL signals were stored in a PC. The duration of all recorded time series was 0.4 ms.

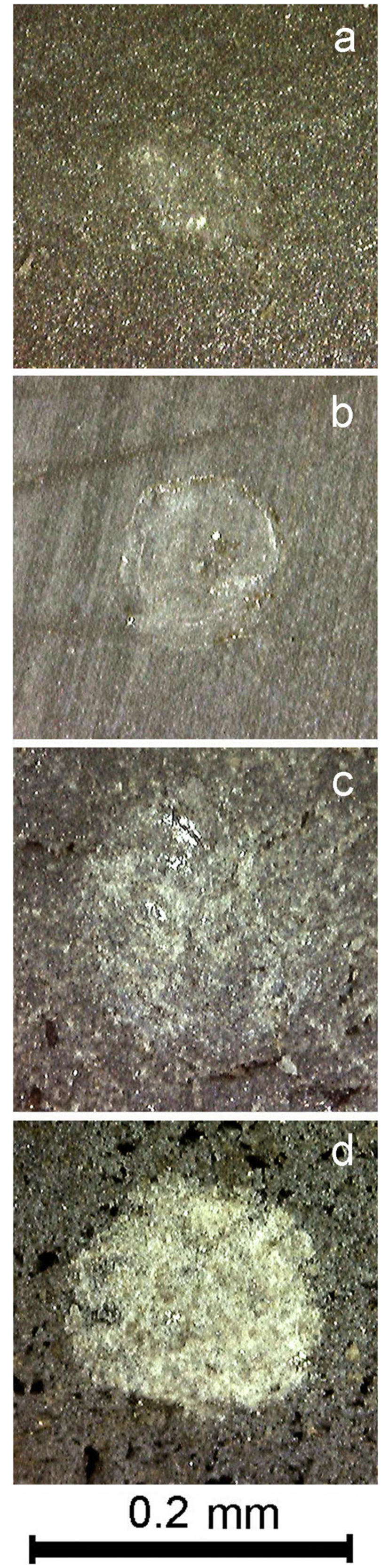

Fig. 2. Photographs of the surface damages on the samples SiC1 (a), SiC2 (b), SiC5 (c), and SiC9 (d).