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Plastic deformation of polycrystalline alumina introduced by scaled-down drop-weight impacts

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ABSTRACT

We present our findings after scaled-down drop-weight tests, performed under relatively low loading conditions and employing a small-scale spherical indenter as a projectile, to boost the strain rate and energy density of the impact, resulted in the generation of a cavity of measurable depth on the surface of a pure, fully dense, alumina ceramic. We demonstrate that activated dislocations are a main contributor in the formation of the residual impression with an estimated maximum density of $\sim 4.02 \times 10^{14}\ \mathrm{m}^{-2}$.

1. Introduction

Since Longy and Cagnoux's paper demonstrating that, along with the fragmentation, dislocations/twins are activated during high-velocity impacts [1], a handful of researchers have paid specific attention to the role that plastic deformation plays in the performance of armour ceramics under various high-impact loading conditions [1–10]. In these investigations, several methods, including gas gun tests [2], flyer plate impact tests [1,3–5] and split Hopkinson pressure bar tests [6,7], were employed. The principle of each of these experiments is the utilisation of a high-velocity projectile/bar ($100–800\ \mathrm{ms}^{-1}$) in order to achieve a peak internal stress beyond the Hugoniot elastic limit, a stressing condition necessary for the initiation of dynamic plasticity [4]. From a practical standpoint, the adoption of such extreme conditions is often a financially costly, labour-intensive and lengthy process. Consequently, despite the potential findings that could be extracted from the data, many researchers and engineers do not typically evaluate plasticity in ceramics under dynamic impact conditions. Ultimately, this limits the scope of the work performed on applications involving dynamic impacts in ceramics. In addition to the cost and time constraints, the resultant impacts from the aforementioned experimental techniques frequently lead to catastrophic failure of the tested specimen. This invariably means that post-impact characterisation requires some form of reconstructive fragment analysis [10], leading to difficulties in interpreting the data. As a result, to date, the analysis of the plastic deformation in armour ceramics has not been understood to a level whereby the conditions of such a physical process and its potential impact on the dynamic/ballistic contact damage resistance of ceramic structures can be clearly defined.

The objective of the present work is to demonstrate the potential of low-velocity drop-weight (DW) impact tests as a simple, convenient and repeatable technique for studying plasticity in ceramics subjected to dynamic impacts. In doing so, we aim to expose a phenomenon after recent DW tests performed on fully-dense monolithic alumina ceramics generated a crater of marked depth and a residual damage zone far beyond anything produced by comparable quasi-static indentation tests. Despite similar DW setups and other "dynamic indentation" tests being performed by other workers [11–13], this response of the material remains undocumented. We believe that, once instrumented, such a method could be useful in helping us understand dynamic damage in different ceramics, as well as provide a viable method for screening armour, aerospace and dentistry ceramics for better performance in advanced ceramic research.

2. Experimental procedure

The alumina test samples were prepared as follows. Ultra-fine, 99.99% pure α-Al_2O_3 powder (TM-DAR, Taimei, Japan) was first ball-milled in butanol (Sigma Aldrich, USA) for 24 h. This slurry was then dried, crushed and ground, followed by sieving. The

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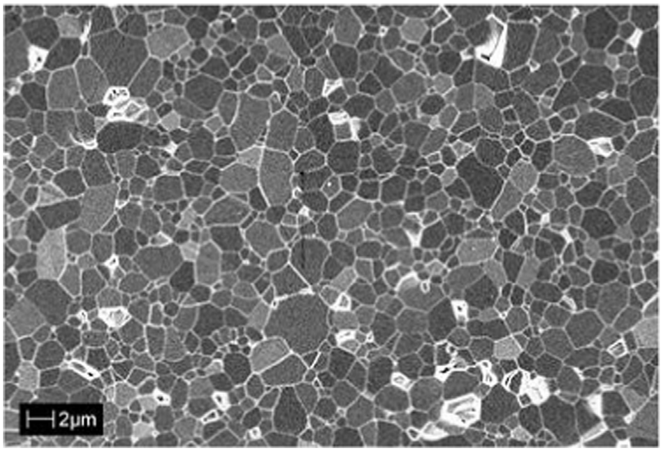

Fig. 1. SEM micrograph of the alumina microstructure after 1 μm polishing and thermal etching.

resultant powder was then die-pressed at ~65 MPa, to form a 40 mm diameter disc with an approximate thickness of 12 mm. These discs were subsequently placed in an isostatic-press at ~200 MPa, followed by sintering in a box furnace. The sintering profile included a ramp rate of 5 °C/min from room temperature to 1050 °C, dwelled for 10 h, then to 1400 °C, dwelled for 4 h. As shown in Fig. 1(a), this produced a 99.5% dense ceramic with an equiaxial grain structure and an average grain size of 1.38 ± 0.73 μm. The sintered alumina samples were then polished using a 1 μm diamond abrasive before DW tests were conducted.

The DW tests themselves were performed using a 2 mm tungsten carbide (WC) ball. A photograph of the testing apparatus used is presented in Fig. 2(a). Prior to DW testing, the unconfined alumina sample was positioned directly on top of a securely fastened thick alumina block (~50 mm thick) and held in place using vacuum grease. For each test, a weighted load of 0.6 kg (5.88 N) was released from a height of ~0.5 m along rails, giving an estimated velocity of ~3.13 ms^{-1}. In this study, a total of 5 single hit tests were performed at different sites across one sample (~30 mm in diameter and ~10 mm in thickness). All test site locations were evenly distributed around the middle of the sample with a separating distance of ~10 mm. This is ~20 times larger than the diameter of the resultant crater size, typically 0.5 mm for this impact load. We believe the aforementioned clearance between each test site was large enough to ensure an independent response in the ceramic during each impact. Frames from a high-speed camera video, taken on a HyperVision HPV-1 (Shimadzu, Kyoto, JPN) at 20,000 frames per second, demonstrates the DW process in Fig. 2(b–e), showing the indenter impacting the surface and the generation of a crater. Strain rate estimations of these impacts, assuming an initial contact diameter of 0.2 mm on impact, indicate that a falling speed of 3.13 ms^{-1} can give a peak strain rate along the surface of $>10^4\ s^{-1}$, which is around the upper boundary for Hopkinson bar tests [14]. The total kinetic energy (KE) applied on contact is calculated at 2.94 J. This is a relatively low value compared with gas gun tests (10–150 J) and ballistic tests (500–4500 J). However, the benefit of having less KE to dissipate is that the residual damage zone remains intact with limited fracturing, making thorough post-testing analysis possible. In order to measure the geometry of the residual impressions produced, a 3D optical microscope (NewView 5000, Zygo Corp., USA) was used to compose 3D surface plots of the individual impressions.

Further post-impact analysis of the impressions involved examination under SEM (Leo 1530 VP, Carl Zeiss, Oberkochen, GER) and optical microscope (DMRX, Leica, Wetzler, GER). Meanwhile, lattice plastic deformation was detected and quantified using Cr^{3+}/Al_2O_3 fluorescence spectroscopy across a single impact site. Fluorescence microscopy was performed using a true confocal Raman microscope (Horiba, Japan) over a spectrum of 14,250–14,550 cm^{-1} with a 633 nm red line He-Ne laser. A 50× objective lens was used in conjunction with a confocal setup that involved two 50 μm pinhole apertures at 90° to one another. This provided an approximate beam diameter on the specimen surface of 1 μm and ensured that data was only taken from the near-surface. A step size of 25 μm was used for measurements taken over ¼ of the impression. Each scan was made twice at each point for 10 s and then averaged, giving a total detection time of 20 s. In order to

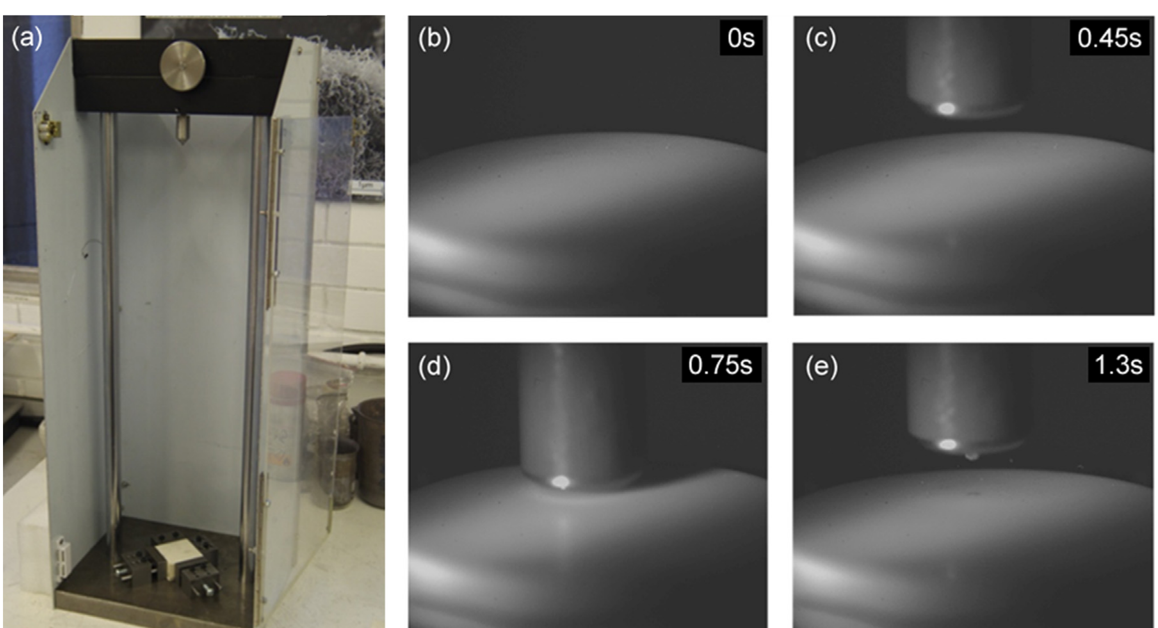

Fig. 2. The DW test apparatus; (a) a photograph of the DW test rig, (b–e) frames taken from high-speed camera footage of the DW impact process; (b) shows the sample prior to damage; (c) at 0.45 s the impacting head comes into view, this is travelling at 3.13 ms^{-1}; (d) at 0.75 s the blunt indenter hits the surface with an impact energy density of ~94 MJ/m^2 (assuming a 0.2 mm contact diameter); (e) at 1.3 s the load bounces back leaving the residual impression generated on the samples surface.