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High strain rate indentation-induced deformation in alumina ceramics measured by Cr^{3+} fluorescence mapping

C.E.J. Dancer[a,*], H.M. Curtis[a], S.M. Bennett[a], N. Petrinic[b], R.I. Todd[a]

[a] *Department of Materials, University of Oxford, Parks Road, Oxford, OX1 3PH, UK*
[b] *Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK*

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Abstract

Alumina materials with a range of grain sizes and purities were subjected to small-scale dynamic impact by sharpened tungsten carbide projectiles at sub-ballistic velocities. The resistance of the materials to fracture was recorded by visual examination of the cracking on the impacted surface and the damage in the subsurface region. The residual stress and plastic deformation induced in each material were examined using Cr^{3+} fluorescence mapping. A modified Hertzian indentation model of the stress state in the material with the addition of a blister field representing the stress induced by the presence of the subsurface plastic zone was found accurately describe the observed cracks beneath the surface of the material, as well as the radial cracks on the surface.

Keywords: Armour; Al_2O_3; Mechanical properties; Plasticity; Residual stress

1. Introduction

Alumina has been used as an armour material since the 1970s[1,2] because it has low density, can be produced by inexpensive processing methods and is sufficiently durable to defeat many types of incoming projectile.[3,4] Alumina tiles are able to defeat these by a number of mechanisms including shattering or blunting the projectile, and dissipation of the energy of the projectile by the cracking and/or plastic deformation of the ceramic. In addition, comminuted material can erode the projectile, reducing it in size or completely destroying it.[5,6]

Alumina has been extensively studied by a variety of high strain rate tests to assess its performance as an armour material.[7–9] However, the possibility of investigating material response at a microstructural scale following tests carried out at ballistic velocities is generally limited due to the destructive nature of the tests. The complicated processes involved make it difficult to correlate individual quasi-static measures of material properties such as fracture strength or toughness to the behaviour of the material under dynamic conditions.[10] Tests are also often limited to a small number of materials, and so it is difficult to correlate material characteristics of alumina such as purity, grain size and density with performance under dynamic impact. Anderson et al.[11] conclude from tests on alumina samples with 3 different grain sizes that samples with a smaller grain size have superior resistance to impact by tungsten carbide spheres at velocities between 10 and 70 m/s. For these velocities there is no discernible rate dependence on the level of damage sustained, although the size of the impact crater increases with impact velocity, as would be expected from analogy with quasi-static indentation since the effective load on the specimen increases with the impact velocity. Lankford[12] demonstrated that a significant increase in compressive strength occurs only above a certain critical strain rate, measured as $>10^3\ s^{-1}$ for Al_2O_3 samples with a grain size of 25 μm.

Material behaviour during indentation tests made under quasi-static conditions (described by Lawn and Wilshaw[13]) does not correlate well with performance under dynamic conditions. In dynamic impact, failure is caused by the coalescence of many micro-fractures which are activated at high strain rates[14] to accommodate the strains generated by plastic deformation.[15] Lankford et al.[16] attribute the extent of plastic deformation achievable prior to failure to the pre-existing flaw population (*e.g.* pores and glassy grain boundaries) in the alumina

* Corresponding author. Tel.: +44 1865 273787; fax: +44 1865 273789.
E-mail address: claire.dancer@materials.ox.ac.uk (C.E.J. Dancer).

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specimen. Alumina specimens show elastic or inelastic responses to dynamic impact, depending on the velocity of impact and the microstructure of the specimen.[15]

For quasi-static indentations, the position and width of Cr^{3+} luminescence peaks in alumina can be related to the residual stress and the extent of plastic deformation in the ceramic, respectively,[17,18] providing the background stress field does not vary over the collection volume. This condition is met for materials, such as those studied here, where the magnitudes of any residual stresses present in the as-sintered material (before any deformation has been carried out) do not vary significantly between randomly chosen points on a sample, so that the measured change in Cr^{3+} R1 peak position in the indented specimen is due solely to the indentation made by indenter. By collecting spectra at points across the sample surface this technique has previously been used to study the deformation caused by quasi-static indentations.[17,19] This work extends the technique to the study of indentations produced by a sub-ballistic velocity dynamic impact test. Using a sub-ballistic velocity (c. 100 m/s rather than c. 700–800 m/s for a ballistic test[3]) allows recovery of intact specimens so that the deformation processes which occur during impact can be studied and compared with models for quasi-static indentations. In addition, the tests in this work use a projectile with similar shape and material to armour piercing bullets, rather than, for example, the well-defined sharp Vickers indenter or blunt spherical Hertzian indenter. This allows the results of this work to be directly compared to the effects of ballistic impact on alumina materials, such that damage processes characteristic of the indenter shape but not necessarily of the impact velocity can be determined.

2. Experimental methods

Alumina discs were produced using either TM-DAR powder (Tai-Mei, 99.99% purity, 100 nm particle size) or AES11c powder (Sumitomo, 99.9% purity, 500 nm particle size). For two TM-DAR specimens 0.25 wt% MgO to inhibit grain growth and 2.1 wt% of organic dispersant (Dispex A40, Allied Colloids) were added to the alumina powder and mixed by attrition milling in water (Szegvari 01HD attrition mill, yttria-stabilized zirconia tank and blade and 3 mm diameter zirconia balls) for 2 h. Powders were freeze-dried and calcined for 1 h at 600 °C to remove the dispersant before uniaxial pressing at 54 MPa and sintering at 1550 °C for 2 h in air (A) or vacuum (B). A third TM-DAR specimen (C) and the AES11c samples (F) were produced from the as-purchased powders after uniaxial pressing at 54 MPa and sintering in air at 1550 °C for 2 h. The AES11c samples (F) were additionally cold-isostatically pressed at 150 MPa between the uniaxial pressing and sintering stages. Following sintering the discs were all approximately 25 mm in diameter and 5 mm in thickness. In addition similar discs of two debased alumina materials were provided by Morgan Technical Ceramics. These contained approximately 5% (D) and 2% (E) glassy phase, and were studied to provide a contrast to the much purer TM-DAR and AES11c samples (for which no glassy phase was visible in SEM micrographs), in order that the effects of both grain size and glass content could be compared to impact behaviour. At least 3 specimens of each type were tested under impact. The grain size was measured from SEM images (JEOL 6300 and Carl Zeiss EVO LS15) of a polished and thermally etched cross-section of each sample using the linear intercept method with a geometric multiplying factor of 1.56. The density was measured by the Archimedes method using distilled water. A summary of the processing conditions and microstructural characteristics of the samples used in this work is given in Table 1.

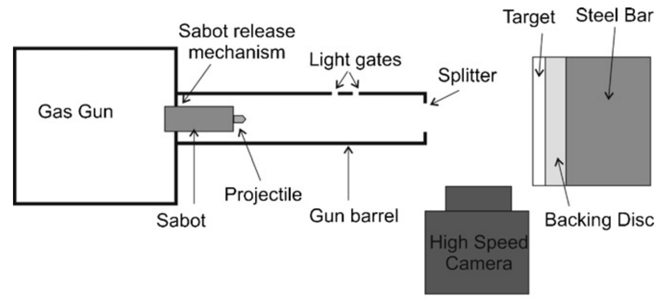

Fig. 1. Dynamic impact test setup.

Prior to high strain rate and quasi-static impact testing, the surfaces of the discs were lapped and polished to a 3 μm finish using diamond pastes. This was required to minimise noise in the optical fluorescence spectra obtained after impact testing.

High strain rate impact tests were carried out by firing sharpened projectiles at polished ceramic discs using a gas gun (Fig. 1). Tungsten carbide cermet (Tungstcarb products, grade K20, 3 mm diameter) rods were sharpened using a diamond-coated glass engraving tool to produce sharp projectiles similar to the cores of armour piercing bullets. Projectiles had an average mass of 0.46 g and tip angle of 45°. Tip sharpness was measured using 3D optical microscopy (Alicona InfiniteFocus) (Fig. 2) and projectiles were rejected if the tip diameter was greater than 200 μm. The average diameter of the tip was c. 100 μm, measured from 3D optical micrographs. All alumina discs were glued (UHU all-purpose glue) to a thick backing disc of alumina to avoid failure by bending at the back surface and mounted to a steel bar of similar diameter to the samples using a small amount of vacuum grease. The sharpened tungsten carbide projectile was attached to a nylon sabot and fired towards the samples over a distance of approximately 2 m using the gas gun. The sabot and the projectile were separated before impact by means of a splitter. The velocity was measured using light gates and was adjusted by control of the gas pressure to approximately 100 m/s. Tests were filmed using a high speed camera (Phantom 7, Vision Research, USA).

Following impact the craters on specimens were examined by scanning electron microscopy (JSM6300, tungsten filament and Carl Zeiss EVO LS15, LaB_6 filament). The indentation volume was measured using a 3D optical microscope (Alicona InfiniteFocus) in “cutting plane mode”. An average position of the surface height around the indentation was recorded and the volume of the void below this depth was measured, subtracting where necessary the volume of any material protruding above the surface level. The surface level (the “cutting plane”) was measured at some distance away from the indentation.