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The correlation of indentation behaviour with ballistic performance for spark plasma sintered armour ceramics

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Abstract

The Knoop and Vickers indentation behaviour of spark plasma sintered SiC–5 wt.% B_4C, B_4C and SiC–2.5 wt.% AlN–3 wt.% C armour ceramics have been investigated and observations correlated with ballistic performance. Surface and sub-surface indentation-induced damage has been characterised via cross-sectioning and serial ceramographic polishing techniques. The nature of the damage appears to be less influential than hardness in relation to ballistic performance, but variability in indentation behaviour appears to correlate with variability in ballistic performance. Examination of the indentation size effect curves shows that both Knoop hardness and predicted transition velocities correlate with V50 ballistic performance against an armour-piercing threat, further supporting the importance of hardness and the potential for indentation to be used as a screening method for armour materials.

Keywords: Ceramic armour; Indentation behaviour; Hardness; Plasticity; Ballistic performance

1. Introduction

Ceramics have been used for ballistic protection against high kinetic energy threats primarily due to their high hardness and ballistic mass efficiency compared with conventional metallic armour materials. However, beyond these general requirements, limited information exists to direct material development. This is highlighted by the "make and shoot" iterative process typically employed to determine correlations between material properties/characteristics and ballistic performance, which is time and resource intensive. There is, therefore, a requirement for simple, low cost screening techniques that can be undertaken on small-scale samples to identify promising novel materials earlier in the development process.

The importance of high hardness in armour ceramics is widely acknowledged[1,2] with numerous studies reporting a positive correlation with ballistic performance against small-calibre threats.[3,4] However, this correlation does not always exist[5,6]; the importance of ceramic plasticity[1,7] and fragmentation behaviour[8,9] are also being highlighted as important influential parameters.

Recent Knoop indentation studies have attempted to semi-quantify a measure of plasticity from indentation size effect curves.[10,11] These values, in combination with hardness, have been shown to correlate with experimentally obtained transition velocities (the impact velocity corresponding to the transition from projectile dwell to penetration) measured by Lundberg and Lundberg.[12] The ability of a ceramic to sustain projectile dwell (i.e. projectile erosion on the ceramic surface with minimal penetration) is an important phase governing overall ballistic performance.[13–15] However, a chemical vapour deposition SiC has been reported as having a measured transition velocity (against WC spheres) higher than that of SiC–N (a leading armour-grade ceramic), but the subsequent penetration resistance at higher velocities is lower, which has been attributed

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to differences in their impact-induced damage.[16] This suggests that the on-set, evolution and type of damage that forms upon impact may play a critical role in the performance of ceramic armour materials both during dwell and after the dwell period ends. This work therefore attempts to characterise the evolution of indentation-induced damage in three different armour-grade ceramics. In addition, hardness and quasi-plastic deformation parameters are correlated with, and used to explain differences in, ballistic performance against a high-velocity armour-piercing projectile.

2. Materials

Disc-shaped samples 60 mm diameter × 6 mm thick of three different materials manufactured by Spark Plasma Sintering (SPS) at Nanoforce Ltd., UK were investigated. SPS was chosen due to its capability of producing finer grain sizes (related to hardness) and higher relative densities compared with more conventional sintering methods. Materials were: (1) B_4C, (2) a SiC–5 wt.% B_4C and (3) a SiC–2.5 wt.% AlN–3 wt.% C sample (sourced from Imperial College London that had been processed to form an aluminosilicate grain boundary phase to encourage intergranular fracture, similar to the fracture behaviour of SiC–N[17]). Commercially available powders of SiC (UF-10) and two different grades of B_4C (HD03 and HD20) purchased from H.C. STARK, Germany were used as starting powders. UF-10 and HD03 powder grades were used to manufacture the SiC–5 wt.% B_4C sample and HD30 to manufacture the B_4C sample. Powders for all three samples were transferred into graphite dies and cold pressed to 3 tonnes (9.4 MPa) using a hydraulic press before wrapping the die in carbon insulating foam to reduce heat loss. The die assembly was then inserted in the SPS furnace (HPD 25/1 FCT Systeme, GmbH) and processed at 1980 °C under 60 MPa pressure. Powder processing details for SiC–AlN–C are reported elsewhere.[18]

3. Experimental methods

3.1. Characterisation

Elastic moduli were calculated by measuring longitudinal and shear wave velocities on 60 mm diameter lapped samples using the pulse-echo reflection method with a transducer couplant gel. Average wave velocities from 5 and 10 MHz longitudinal and shear wave transducers were measured. Sample thicknesses were measured using a micrometer (±0.01 mm). Elastic moduli and Poisson's ratio values were calculated using Eqs. (1)–(3) with estimated uncertainties calculated by propagation of error analysis.

$$E = \frac{(C_l^2 \times \rho \times (1+\upsilon)) \times (1-(2\times\upsilon))}{(1-\upsilon)} \quad (1)$$

$$\upsilon = \frac{1-\left(2\times\left(\frac{C_s}{C_l}\right)^2\right)}{2-\left(2\times\left(\frac{C_s}{C_l}\right)^2\right)} \quad (2)$$

$$G = \frac{E}{\left(\frac{1+\upsilon}{2}\right)} \quad (3)$$

where E is the Young's modulus, G is the shear modulus, C_l is the longitudinal wave velocity, C_s is the shear wave velocity and υ is the Poisson's ratio.

Sample discs were sectioned across their thickness to check for microstructural inhomegenity and a segment removed for density determination. An additional smaller specimen approximately 5 mm × 10 mm in size was cut from the centre of each sample and mounted together in an alumina-reinforced epoxy resin and polished to a 0.04 μm surface finish for indentation examination. Density measurements for each ceramic specimen were obtained using the Archimedes' immersion method using a Sartorius LA230 microbalance (±0.001 g). De-ionised water was used as the immersion fluid and was kept at a constant temperature of 20 °C. The density of the fluid was recorded as 0.998 g cm^{-3} at 20 °C. Theoretical densities (TD) of the materials were calculated using the rule of mixtures taking the TD of SiC, B_4C, AlN and C as 3.210 g cm^{-3},[19] 2.520 g cm^{-3},[20] 3.3 g cm^{-3},[21] and 2.267 g cm^{-3},[22] respectively. Polished mounted samples were sputter coated with 2 nm of gold prior to imaging surfaces using a scanning electron microscope (SEM) (JEOL-7100F) in backscattered electron (BE) detector mode.

3.2. Indentation behaviour

Knoop (HK) and Vickers (HV) hardness were measured on sectioned samples polished to a 0.04 μm surface finish using a FM-100 micro-hardness tester (FUTURE-TECH CORP) at loads (F) of 0.98, 1.96, 2.94, 4.91, 9.81 and 19.6 N at ambient conditions in accordance with ASTM standards C1326-08e1[23] and C1327-08[24] with an approximate dwell time of 15 s. Ten valid indentations were measured and hardness values recorded prior to determining the mean hardness. A measure of Knoop indentation plasticity was semi-quantified using the gradient of the indentation size effect (ISE) curve as proposed by McCauley and Wilantewicz,[10] by plotting $\log_{10}$ HK against $\log_{10}$ F, whereby a shallow ISE represents a material that exhibits greater plasticity under indentation. Predicted transitional velocity values were calculated using Eq. (4) taken from Hilton et al.[11] based on the relationship between HK(1 N) + plasticity and experimental transitional values of three SiC ceramics (Eq. (4)).

$$\mathrm{TV} = 33.59\left[\mathrm{HK}(1\quad \mathrm{N}) + \mathrm{Abs}\left(\frac{1}{c}\right)\right] + 261.42 \quad (4)$$

where TV is the predicted transition velocity (m s^{-1}) and Abs(1/c) is the semi-quantified measure of plasticity derived from the gradient (c) of the Knoop ISE curve.

Sub-surface indentation-induced damage across all three materials was examined simultaneously by mounting the samples together and using two different techniques; serial ceramographic polishing and cross-sectioning across the mid-point of 19.62 N Vickers indentations. Serial ceramographic

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