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Short Communication

Sub-scale ballistic testing of an ultrafine grained tungsten alloy into concrete targets

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ABSTRACT

Ultrafine grained tungsten-based alloys are promising kinetic energy penetrator materials because of their high strengths and densities, making them ideal for penetration into concrete and geomaterials. However, there are difficulties in evaluating their ballistic performance using traditional testing techniques because ultrafine grain sizes are challenging to achieve in bulk parts. In this letter, we performed sub-scale ballistic experiments where ultrafine tungsten alloy cores were fired into concrete targets using small caliber projectile assemblies. The results suggest that sub-scale testing may be used as a screening tool for advanced kinetic energy penetrator materials that are more easily prepared in smaller geometries.

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1. Introduction

High-density alloys with ultrafine and nanocrystalline grain sizes possess a unique set of mechanical properties that make them very attractive kinetic energy penetrator materials for rigid body penetration into concrete and geomaterials. Their high strengths, for instance, suggest that they should remain elastic at incident velocities where penetrators made from softer materials, e.g., high strength steels, start to deform plastically [1–3].

Despite such promising properties, there have been few experimental studies evaluating the ballistic performance of these ultrafine grain penetrator materials. One reason for this is that many of the standard protocols for characterizing penetration performance call for penetrators with dimensions that are difficult to achieve in parts with ultrafine grain sizes. For example, the Forrestal framework for evaluating the performance of rigid body penetrators into concrete was originally developed for penetrators with lengths upwards of 8 cm and diameters of at least 1 cm [4]. But it is difficult to make ultrafine grain parts this large because of engineering constraints on workpiece dimensions in relevant processing routes.

In the present work, we use an alternate approach, evaluating the ballistic performance of an ultrafine grain tungsten alloy using small-caliber, spin-stabilized projectiles fired into concrete targets. Our results demonstrate the potential of sub-scale ballistic tests as a means of characterizing next-generation kinetic energy penetrator materials.

2. Materials and methods

2.1. Penetrator materials

We studied the ballistic performance of two different penetrator materials: a tungsten carbide cermet (WC—12Co, wt%) and a powder-processed, ultrafine-grained W alloy. A schematic of the cemented carbide penetrator is shown in Fig. 1a. We used these conical nose cemented carbide rounds to calibrate the penetration equations described below. Quasi-static compression tests on specimens machined from these cemented carbide rounds gave an average failure stress of 3.8 GPa, with the samples failing by brittle fracture. The cemented carbide cores had a mass of 2.1 g and a specific gravity of 14.3 g/cm^3.

We also prepared sub-scale rounds from an ultrafine-grained W—Cr—Fe alloy whose chemistry and processing schedule were based on Ref. 2. The material used in this study was prepared by 6 h of attrition milling of elemental feedstock powders of W and Cr (99.95 pct W –100 mesh; 99 + pct Cr, –325 mesh) with an initial stoichiometry of W—10Cr, at%. Milling was performed under an Ar atmosphere using 200 g of powder, steel media, and a ball to powder ratio of 10:1. The final chemistry of the as-milled powder was

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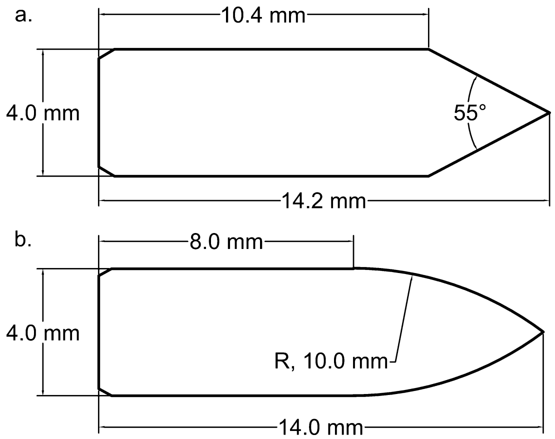

Fig. 1. Schematics of the (a) cemented carbide and (b) W—8Cr—4Fe penetrators.

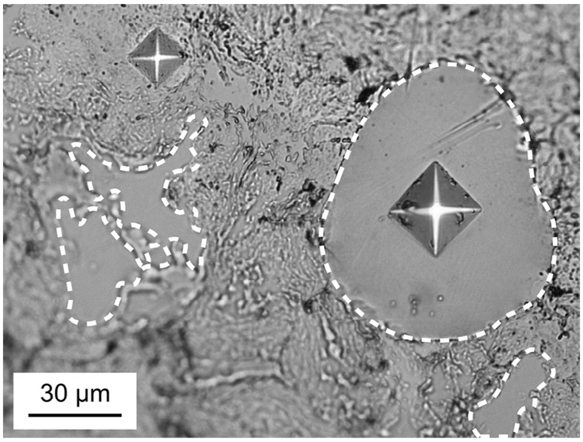

Fig. 2. Optical micrograph of Vickers microhardness impressions in the coarse- and fine-grained regions. The softer, coarse-grained regions are indicated by the dashed white lines.

W—8Cr—4Fe, at% as measured by energy dispersive spectroscopy, where the Fe was introduced due to abrasion of the milling equipment. We consolidated the as-milled powder using a Dr. Sinter SPS-515S hot press, a graphite punch and die having a diameter of 24 mm, and the preferred consolidation parameters identified in Ref. 2: a ramp rate of 100 K/min, a consolidation pressure of 100 MPa, a soak time of 1 min, and a soak temperature of 1200 °C. We then centerless ground samples electro-discharge machined from the center of these compacts into ogive nose rounds with the dimensions given in Fig. 1b.

We mounted in epoxy, cross-sectioned, and polished one of these W—8Cr—4Fe rounds using standard metallographic techniques, and characterized the microstructure of this cross-sectioned round using a JEOL 6610LV scanning electron microscope (SEM) operated at 20 kV and equipped with an energy dispersive spectrometer. We also measured this cross-sectioned round's Vickers microhardness using a LECO microhardness tester with a load of 100 gf and a hold time of 15 s. These microstructural investigations revealed that the W—8Cr—4Fe penetrators had a bimodal grain size distribution: approximately 85 vol% of the penetrator had a grain size of 200 nm, while the remaining material was coarse grained, with an average grain size exceeding 10 μm. As a result of their different grain sizes, the coarse- and fine-grained regions had different mechanical properties, with the fine grained regions having an average Vickers hardness of 10.8 GPa, more than double the Vickers hardness of the softer, coarse-grained regions. This difference in hardness is illustrated by the optical micrograph in Fig. 2, which shows residual microhardness impressions in the coarse- and fine-grained regions. The coarse- and fine-grained regions also had different chemistries: the coarse-grained regions contained nominally pure W, while the fine grained regions contained W and the solute elements Fe and Cr, with an average stoichiometry of W—10Cr—6Fe as measured by energy dispersive spectroscopy.

These ultrafine grain tungsten penetrators had an average mass of 2.3 g, an average stereological porosity of 6%, and a specific gravity of 16.1 g/cm^3 as measured by the Archimedes method using high purity water as a reference liquid.

2.2. Ballistic test method

In the ballistic tests, we inserted the cemented carbide or the W—8Cr—4Fe core into a thin aluminum cup and copper jacket to increase the diameter to 5.56 mm. We then fired each assembly from a 5.56 mm diameter powder gun with a 1:7 twist and a 0.5 m long barrel, and varied the penetrators' incident velocities between 500 and 1100 m/s by varying the gun powder charge. We monitored the incident velocity as well as the pitch and yaw at impact using flash x-radiography [5]. Based on these flash x-ray measurements, we adjusted the muzzle-to-target distance between 3.3 and 3.9 m to minimize the pitch and yaw at impact, and only included tests with angles of incidence less than 4° in our analysis.

We fired all of the shots into targets prepared from the same batch of well-cured concrete. The concrete had a density of 2.2 g/cm^3 and contained aggregate with a volume-average, circular equivalent diameter of 2 mm. Cylindrical compression specimens with a 5 cm diameter and an aspect ratio of 2.5 that were cored from several targets had an average, unconfined compressive failure strength of 48 MPa. The concrete targets had cross-section dimensions of 20 by 20 cm and a thickness of 13 cm.

We measured the depth of penetration from the target's impact surface to the embedded penetrators' nose using static, post-test radiographs of the targets. The reported depths of penetration are the average of two measurements from radiographs taken at right angles to one another, which were generally in good agreement. The maximum depth of penetration that we measured was roughly half the thickness of the target and there was no scabbing seen on the back face of the target after impact, so these targets could be approximated as semi-infinite.

2.3. Forrestal analysis of ballistic results

To analyze the ballistic results, we used a framework developed by Forrestal and coworkers to describe rigid body penetration into concrete and geomaterials [4,6–17]. These researchers showed using penetrators with on-board accelerometers that the axial force on a projectile during impact can be described by the following relationships:

$$F = -cz \quad z \le 4R \tag{1a}$$

$$F = -\pi R^2\left(\sigma S + N\rho V^2\right) \quad z > 4R \tag{1b}$$

where Eqns. (1a) and (1b) describe the force equations during the cratering and tunneling phases of impact, respectively, and with c, S, and N constants that are defined below, z the instantaneous depth of penetration, R the radius of the penetrator, σ the unconfined compressive stress of the concrete target, ρ the density of the concrete, and V the instantaneous velocity of the penetrator [14,15,17].

The pre-factor c in Eqn. (1a) is a constant that depends on the incident velocity, V_S, as follows: