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Penetrating performance and "self-sharpening" behavior of fine-grained tungsten heavy alloy rod penetrators

Rongmei Luo [a,b,*], Dewu Huang [b], Mingchuan Yang [b], Enling Tang [b], Meng Wang [b], Liping He [b]

[a] School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing 210094, Jiangsu, China
[b] College of Equipment Engineering, Shenyang Ligong University, Shenyang 110159, Liaoning, China

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ABSTRACT

Rod penetrators with 95W–3.75Ni–1.25Fe fine-grained tungsten heavy alloy (fine-grained 95W) and conventional tungsten heavy alloy rod penetrators with the same chemical composition (conventional 95W) were subjected to ballistic impact to compare their penetration performance. "Self-sharpening" behavior and an average 10.5% increase in penetration depth compared to conventional 95W penetrators. An acute head remained on the fine-grained 95W rod with SEM results revealing many micro-cracks and small debris on surface layer of the rod head. The stress-strain curves collected in the Split Hopkinson Pressure Bar (SHPB) experiment showed that critical failure strain values of the fine-grained 95W were 0.12 and 0.39 at strain rate of $2 \times 10^3\ s^{-1}$ and $3.9 \times 10^3\ s^{-1}$, respectively, approximately 40% and 10% lower than those of the conventional 95W. The dynamic strength values of fine-grained 95W were 2100 MPa and 2520 MPa, respectively, which were 500 MPa and 520 MPa higher than those of the conventional 95W. The relationship among microstructure, mechanical property and "self-sharpening" behavior of fine-grained 95W is discussed in this work.

1. Introduction

Rod penetrators have been widely used to destroy tanks, armored vehicles and other armored targets that possess a large specific kinetic energy and large length to diameter ratio [1–3]. With the increase in armor thickness and improvements in armor protection technology, the armor-piercing capacity of rod penetrators needs to be further improved. Currently, tungsten heavy alloys (WHAs) and depleted uranium alloys (DUAs) are the main materials for rod penetrators due to their high density and high strength. The depth of penetration (DOP) of DUA rods is typically increased approximately 10–15% over that of conventional WHA rod under the same experimental conditions [3–5]. The "self-sharpening" behavior, where the head of the DUA rod is viewed as an acute shape, is extensively accepted to explain the deeper DOP [6–8]. In contrast, the head of conventional WHA rods tends to form a mushroom-like shape, which increases the penetration resistance and decreases DOP [9–20]. However, DUA is banned by many countries as it causes serious environmental and health problems with long-term exposure. Consequently, considerable efforts have been made to develop WHA rod materials with "self-sharpening" behavior to improve penetration capability [7–16].

"Self-sharpening" behavior in rod penetrators of WHA materials has been previously reported. For example, WHA rods exhibit "self-sharpening" behavior when formed using severe plastic deformation methods, such as hot hydrostatic extrusion and hot torsion (HE+HT) [15,20], hot-hydrostatic extrusion [21,22], hot-hydrostatic extrusion and cold torsion [23], and swage molding [24]. "Self-sharpening" behavior, with an accompanying 25–50% increase in DOP over conventional 95W is also observed with rod penetrators that consist of a tungsten-fiber/metallic glass matrix composite (WF/MG composite) [16–18]. Recently, a 80W–14Cu–6Zn rod produced by a pressureless infiltration method has shown "self-sharpening" behavior in ballistic impact tests, with a DOP 30% deeper than that of 90W–7Ni–3Fe rods [13,19]. High susceptibility to adiabatic shear bands (ASB) is proposed as the reason for this "self-sharpening" behavior by most researchers [6–12]. However, the 80W–14Cu–6Zn rod maintains an acute head without ASB on the rod remnant, and this "self-sharpening" behavior is explained by its high strength and appropriate critical failure strain [13,19]. Additionally, there are no ASB on the head of the WF/MG composite rod, but an acute head appears on the rod remnant due to shear failure of WF/MG composite [17]. It appears there are may be additional unique mechanisms that give rise to "self-sharpening"

* Corresponding author at: School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing 210094, Jiangsu, China and College of Equipment Engineering, Shenyang Ligong University, Shenyang 110159, Liaoning, China.

E-mail address: luorm_1999@126.com (R. Luo).

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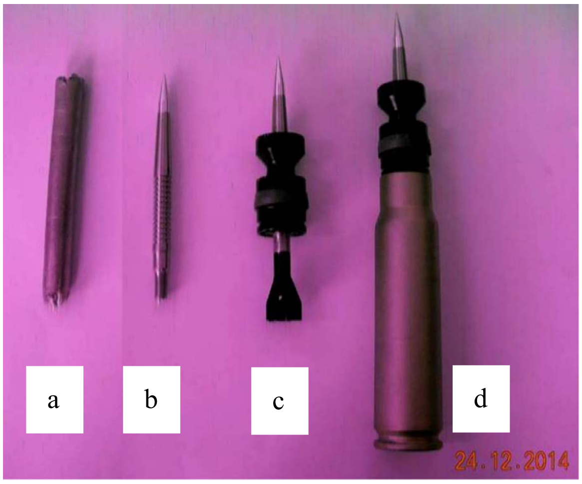

Fig. 1. Photograph of different types of produced samples (a) blank, (b) rod, (c) assembled penetrator, and (d) projectile.

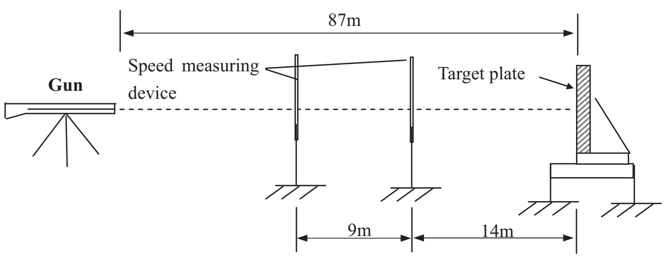

Fig. 2. Schematic diagram of the ballistic impact setup.

behavior during the penetrating process.

Fine-grained WHA is one of the most promising tungsten alloy research subjects, and has shown susceptibility to ASB in some studies [25–29]. However, so far there have been few ballistic tests to demonstrate the "self-sharpening" behavior for the fine-grained WHA penetrator. Kim et al. [26,28] reported that "self-sharpening" was promoted by ASB in the fine-grained WHA penetrator made by mechanical alloying and two-step sintering, however, the penetration performance was not improved compared to the conventional WHA penetrators. In this study, a fine-grained 95W was produced in our laboratory. The ballistic test showed that the fine-grained 95W rod exhibited "self-sharpening" behavior and the DOP improved by approximately 10% compared to the conventional 95W rod. Microstructure and mechanical property analyses were carried out to explain "self-sharpening" behavior, and the relationship among the microstructure, mechanical properties and "self-sharpening" behavior of fine-grained 95W is discussed.

2. Experimental

Rod material of fine-grained 95W–3.75Ni–1.25Fe alloy was fabricated by spray drying and two-stage sintering method in our laboratory following a previously published procedure [25,30]. Rod morphology was observed by ULTRA-PLUS SEM and the chemical composition of the WHA material was analyzed by EDS. The tensile properties of both fine-grained 95W and conventional 95W were measured by an Instron 8872 Fatigue Testing System (USA) at room temperature at a speed of 3.2 mm/min. Compression test was conducted at room temperature using an Instron 5982 at a speed of 2.2 mm/min.

Sintered blanks of both fine-grained 95W and conventional 95W were machined into rod penetrators with a length to diameter ratio of approximately 15 (L/D∼15). Fig. 1 shows the different types of produced samples (a) blank, (b) rod, (c) assembled penetrator and (d) projectile. The target plate was 100 mm thick rolled homogeneous armor (RHA) steel (30CrMnMo). A schematic diagram of the ballistic impact setup is shown in Fig. 2. Ballistic tests were conducted using a 30 mm bore solid-propellant gun placed 87 m in front of the target plate. The impact velocity was measured with a speed measuring device consisting of two layers of Sn-foil separated 9 m from each other positioned 14 m in front of the target. Three rods of fine-grained 95W and three rods of conventional 95W were launched by the gun with velocities ranging from 1200 m/s to 1250 m/s. The test was carried out at 0° obliquity. All rods were embedded into the target plate.

After ballistic impact, the target with embedded rods was retrieved. The remnants and the target with craters were sectioned along the symmetry plane by DK7750 wire electrical discharge machining to evaluate the penetration performance. The sectioned surface of remnant was polished to a mirror finish and etched for further micro-analyses. ULTRA-PLUS SEM and S-3400N SEM were employed to observe the microstructure of remnants and to analyze the "self-sharpening" mechanism of the fine-grained 95W rod penetrator.

The stress–strain relationships of the fine-grained 95W and conventional 95W materials at high strain rate (approximately $10^3\ s^{-1}$) were obtained under uniaxial dynamic compression by a Split Hopkinson Pressure Bar (SHPB) apparatus. The incident and the transmitted bars of the SHPB were made of high strength steel 16 mm in diameter and 2 m in length. The specimen was cylindrical with dimensions of Φ 6 mm $\times$ 5 mm. To reduce the interface friction between the incident bar and the specimen, the specimen surface was lubricated with silicone grease. The average strain rate varied from 2000 s^{-1} to 3900 s^{-1} for the two types of 95W during the SHPB tests.

3. Results

3.1. Characterization of rod material

The SEM morphologies and EDS results of the two types of 95W rod penetrators are shown in Fig. 3. The microstructure of conventional 95W is shown in Fig. 3(a), with a tungsten grain size of approximately 30–50 μm. Fig. 3(b) shows the microstructure of fine-grained 95W rod penetrators with a spherical tungsten grain size of approximately 15–20 μm. There are some micropores and flaws designated with arrows. Tungsten grains are distributed homogeneously within the matrix for both types of 95W. EDS data reveal nearly identical chemical compositions of the two types of 95W. The two types of 95W rod penetrators have similar weight with densities of 17.96 g/cm^3 and 17.92 g/cm^3 for the conventional 95W and fine-grained 95W, respectively. The quasi-static engineering stress-strain curves are shown in Fig. 4 and mechanical properties are listed in the Table 1. From Table 1, it can be seen that the yield strengths are almost equal, while the tensile strength and the elongation of the fine-grained 95W are 775 MPa and 5%, respectively, lower than those of the conventional 95W (1022 MPa and 31%). However, the compressive yield strength of fine-grained 95W is 988 MPa, 247 MPa higher than that of conventional 95W.

Tensile fractographs of the two 95W specimens are shown in Fig. 5. Both 95W show a mixed fracture mode of tungsten cleavage, W–W debonding and matrix rupture. Tungsten cleavage and matrix rupture play are dominant in conventional 95W, whereas the W–W debonding is the main fracture mode for fine-grained 95W.