Tungsten-Titanium Powder Compaction by Impulsive Loading (I)

W-Ti 분말 압축 (I)

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ABSTRACT

Depleted uranium (DU) outperforms tungsten heavy alloys (WHA) by about 10%. Because of environmental and hence, political concerns, there is a need to improve WHA performance, in order to replace the DU penetrators. A technique of metal powder compaction by the detonation of an explosive has been applied to tungsten-titanium (W-Ti) powder materials that otherwise may be difficult to fabricate conventionally or have dissimilar, nonequilibrium, or unique metastable substructures. However, the engineering properties of compacted materials are not widely reported and are little known especially for the "unique" composition of W-Ti alloy. To develop high-performance tungsten composites with superior ballistic attributes, it is necessary to understand, carefully document controlled experimental results, and develop basic computational models for potential composites with controlled microstructures. A detailed understanding and engineering application of W-Ti alloy can lead to the development of new structural design for engineering components and materials.

Key Word : DU Ballistic Penetrator, W-Ti Powder, SHPB, Ultrasonic Wave Velocity.

1. INTRODUCTION

The Asian Wall Street Journal[1] reports that "a furor has been sweeping through Europe in recent weeks over fears that exposure to weapons made from depleted uranium (DU) metal may have put civilians and soldiers at risk for leukemia and other illnesses. Unknown to man, similar concerns are shaking residents of this historic New England community". In a ballistic environment, the material of the penetrator undergoes very large plastic strains (several hundred percent) at very high strain rates (10^5/sec or greater) under high pressures (many GPa's), producing considerable heat due to plastic deformation. Under these conditions, the deformation of a conventional DU penetrator quickly localizes into intense adiabatic shearbands, promoting its penetrability by flaking off and minimizing the size of the impacting face of the penetrator. The efficiency of the penetrator, in general, depends on the manner by which the deformation is localized and the accompanying failure mechanics.

Therefore, the uranium projectile is an efficient penetrator. The DU however, causes health hazards. There is, therefore, a need to replace the DU penetrators with environmentally safe materials[5]. A technique of metal powder compaction by the detonation of an explosive has long been introduced in the engineering material industries. However, details of explosive compacting procedure and engineering properties of the compacted materials are not widely reported and are little known especially for the "unique" composition of tungsten-titanium (W-Ti) alloy. A detailed understanding and engineering application of W-Ti alloy can lead to the development of new structural design for engineering components and materials.

2. WAVE PROPAGATION THEORY

2.1 Wave Propagation Theory

The spalling stress (σ_s) can be approximated by the linear relation between stress and particle velocity (û) as follows, assuming one dimensional stress wave propagation.[12]

$$\sigma_s = C \varphi \hat{u}$$

The longitudinal wave velocity (C) is defined by

$$C_a = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}}$$

for an infinite body, and

$$C_b = \sqrt{\frac{E}{\rho}}$$ for a finite body,

where E is the Young's modulus, ν the Poisson's ratio, and φ the density of the body.

Assuming a spherical charge of the explosive, the amplitude of the explosive pressure decreases as the stress wave propagates away from the center of explosion. The peak pressure (P_r) at distance (r) can be determined by

$$P_r = P_d\left(\frac{a}{r}\right)^n ,$$

where (a) is the radius of spherical charge and n the distance exponent (1.0 at a great distance and 2.0 - 2.2 near the origin). The detonation pressure of an explosive can be approximated by

$$P_d = 2.3 \times 10^{-7} \times V_d \times r \quad ,$$

where P_d is the detonation pressure (kbar), V_d the velocity of detonation (ft/s), and φ the density (g/cc). The length of spall (L) can be estimated by

$$L = \frac{\lambda}{2} \frac{S_t}{P_r} ,$$

where λ is the length of shock wave and S_t the tensile strength of the material. Discussion of this process is beyond the purpose of this paper. Details can be found elsewhere.[2)]

2.2 SHPB Theory

Split Hopkinson Pressure Bar (SHPB) experimental methods have been well introduced in different applications by the authors. [6, 7, 8, 9)]

Dynamic stress-strain curve can be determined in the compression-tension SHPB apparatus and can indicate whether this material shows thermal softening behavior during the plastic deformation. Assuming that the stress across the relatively short specimen is constant, the sample strain rate ($\dot{\varepsilon}$), average strain (ε), and average stress (σ) can be determined by

$$\dot{\varepsilon}\ (t) = \frac{2\ C_b}{L_s}\ \varepsilon_R\ (t)$$

$$\varepsilon\ (t) = \int_o^t \dot{\varepsilon}\ dt'$$

$$\sigma\ (t) = E_b\ \frac{A_b}{As}\ \varepsilon_T\ (t)$$

The detailed experimental procedure and data analyses can be found elsewhere.[7)]

3. SAMPLE FABRICATION

The use of two-phase composites consisting of spheroidal tungsten particles embedded in a nickel-iron matrix has been already published with its adiabatic shear deformation characteristics under dynamic loading case.[6)] It is known that the fabrication of highly refractory nature of tungsten results in time consuming, energy intensive methods. The use of explosive compaction to consolidate and sinter the powdered precursors transforms W-Ti powder into fully dense products. Explosive compaction has been applied to materials that otherwise may be difficult to fabricate conventionally or have dissimilar, nonequilibrium, or unique metastable substructures. Due to the rapid densification rate, these samples often suffer from low nonuniform densities, poor interparticle bonding, and severe cracking.[3, 4, 5)]

A "cup cake" shaped W-Ti alloy (nominal Diameter = 0.778" and Height = 0.281") has been prepared by compacting W-Ti metal powder with an explosive at ARL. Twelve cubic specimens (nominal 5/32 x 5/32 x 5/32") are prepared using a wire EDM. The direction and position of each specimen are shown in Figure 1. Material loss per cut by the wire EDM was approximately 13 thousandth inch. At the U. S. Army Research Laboratory

(ARL), a simpler variant of hot explosive compaction is being applied to the consolidation of W-Ti alloys. In the ARL technique of combustion-synthesis-assisted hot explosive consolidation (CSA-HEC), an in-situ TiC Chemical Furnace is used to preheat the powder. The TiC chemical furnace is a highly exothermic mixture of Ti and C powders that, when allowed to react, will generate heat and temperatures of 3000°C.

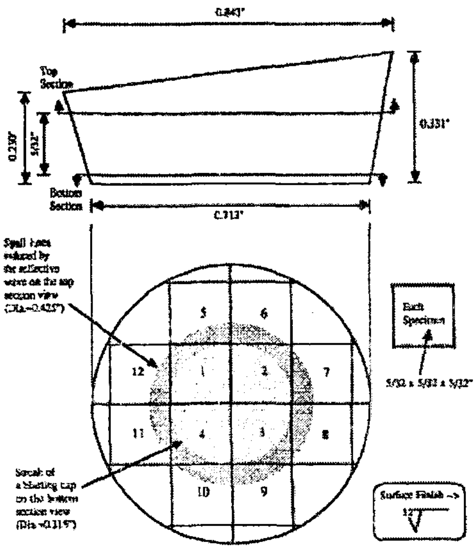

Fig. 1. W-Ti alloy prepared by compacting metal powder with detonation of explosive provided by U. S. ARL and the location of spall lines.

The Amatol (80/20 NH_4NO_3 / TNT) explosive has been placed between the W-Ti powder layer and a blasting cap for the explosive compaction. Details of sample fabrication procedures in the TiC chemical furnace are well described by Kecskes and Hall. [4, 5]

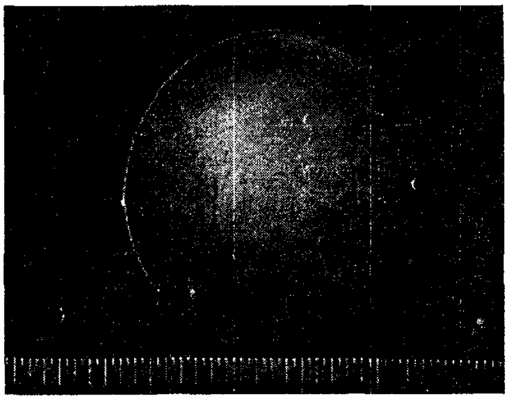

Fig. 2. Fracture line (spall) induced by the reflected wave after detonation (scale in 1 cm) -- top section view.

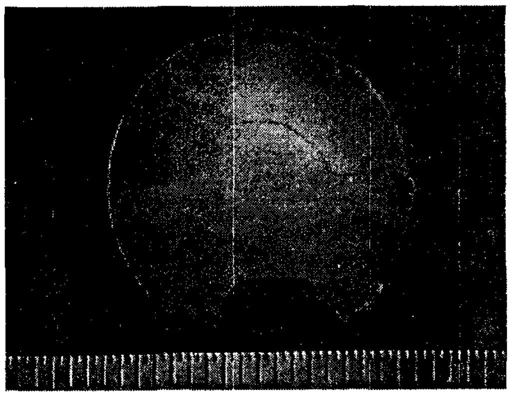

Fig. 3. Fracture line (spall) induced by the reflected wave after detonation (scale in 1 cm) -- bottom section view.

The detonation of explosive produces high amplitude shock waves and high temperature in the W-Ti metal powder. Pressures just behind the shock wave front can be in the order of 1 GPa to 30 GPa, while temperature can rise from 1700°C to 4000°C. Therefore, the metal powder can be easily transformed into a new solid state of W-Ti alloy. Two transverse sections (before preparing twelve test specimens), taken perpendicular to the cylindrical axis of the original material, reveal significant spalling induced by the reflected explosive waves in excess of the tensile strength of the material (Figure 2). The impact of direct loading contact area on the specimen surface can be identified in Figure 3.

A variation in material properties is expected along the radial direction due to the presence of random population of microcracks induced by the reflecting boundary conditions and inhomogeneous loading of the metal powder. Since the specimen dimension is relatively small, it is expected that more complicated interaction of the waves resulting from the transmitting (from the bottom face of the specimen) and reflecting waves (form the top and sides of the specimen) may influence overall properties. This complication can cause additional fractures to the specimen. In order to obtain unbiased measurements, three specimens for each test condition (quasi-static and SHPB experiments) are selected -- one from the middle and two from the outside boundary.

4. EXPERIMENTAL PROCEDURE

The quasi-static experimental laboratory is fully equipped with a tension-compression testing frame (Instron).

4.1 Mechanical Properties of W-Ti Alloy

The quality of metal compaction depends on the shape, intensity, velocity and duration of the pressure wave, initial grain size, void ratio, heat conductivity and melting point of the metal particle, crushability of particle, etc. Due to the excessive heat generated by explosive, the overall engineering properties of W-Ti alloy may be dominated by the central core melting region.

Table 1. Comparison of conductivity and heat capacity of several elements with those of uranium.

Element	Conductivity κ W/cm K	Heat Capacity Cp J/gK
uranium	0.276	0.116
tungsten	1.740	0.132
titanium	0.219	0.523

Uranium has very low heat conductivity (0.276W/cmK). It has low crystal symmetry (orthorhombic), leading to fewer available slip systems than higher symmetry FCC or BCC metals. It also has very low heat capacity (0.116J/gK). Thus, relatively small heating is required to raise the temperature. With the low heat conductivity, the heating remains localized. This leads to local thermal softening and the quick formation of intense adiabatic shear bands. Table 1 compares the conductivity and heat capacity of tungsten and titanium with those of uranium. As is seen, the tungsten in WHA, with its high conductivity, acts as a heat distributor. Furthermore, tungsten has a much lower heat capacity than titanium, but it has a much greater flow stress. Therefore, once tungsten begins to deform inelastically, it quickly heats up, making it easier to participate in the overall deformation. Hence, it stabilizes the flow and hinders the formation of intense, localized shear bands.[6]

No suggestion as to the number of samples necessary for a meaningful statistical analyses is available for metallic materials. Three representative specimens (2, 6, and 7) are selected for this experiment. Isothermal unconfined uniaxial compressive test are performed on each specimen in the Instron testing apparatus for measuring strain hardening curve and static Young's modulus. The test procedure complies with ASTM standard.[10, 11]

4.2 Metallograph

The metallographs of two transverse sections showing fracture and streak of blasting cap are prepared by an optical microscope (Olympus Photomicrographic System, PM-10AD). For a better photograph, these transversely sectioned pieces are impregnated with epoxy (Buehler, Transoptic Powder) and the surface are ground flat, based on ASTM standard.[11]

Since the W-Ti alloy has been prepared by explosive emitting high temperature and shock wave loading, the grain inter-locking structure may be quite different from the steel alloy prepared by a conventional fabrication technique. Therefore, grain structures such as composition, texture, average grain size, etc. can be identified by the SEM. Change in microstructure will be published elsewhere.[8]

4.3 Ultrasonic Wave Velocity

The Longitudinal (P) and transverse (S) wave velocities are measured for all specimens. It is known that P-wave velocity is sensitive enough to detect structural changes in solid materials, while the velocity of S-wave is relatively independent of this change. The P- and S-wave velocities of each finite specimen are measured using one set of transducers (Panametrics -- 5 MHz resonance frequency) and analog oscilloscope (Tektronix, K213).

4.4 SHPB Experiment

The Employment of the dynamic recovery experiment was necessary to understand microstructural change and its effect on the change in mechanical properties of materials. Each specimen is subjected to a pre-assigned shape and duration of loading and then recovered without any additional loading to the specimen. Recovery Hopkinson compression techniques are developed in the Center of Excellence for Advanced Materials (CEAM) at the University of California, San Diego (UCSD), and used extensively to obtain the quasi-isothermal and quasi-adiabatic stress-strain relations for solid materials at high strain rates (> 1000 /sec). Detailed experimental technique and data analysis can be found elsewhere.[9)]

5. RESULT AND SUMMARY

Dynamic properties of powder compacted W-Ti are listed in Table 2.

Table 2. Measured ultrasonic wave velocities of tungsten-titanium (W-Ti) alloy prepared by W-Ti metal powder.

Sample ID	Face-1 (ft/s)		Face-2 (ft/s)		Face-3 (ft/s)	
	Vp	Vs	Vp	Vs	Vp	Vs
WTi-2	12,927	7,209	13,824	7,716	13,824	7,848
WTi-6	12,953	7,178	14,171	7,592	13,934	7,231
WTi-7	15,862	8,229	15,682	8,075	15,388	8,055
Avg.	13,910	7,540	14,560	7,790	14,380	7,710
6061 Al	20,930 for P-wave			10,520 for S wave		

Vp -- Longitudinal (P) wave velocity

Vs -- Transverse (S) wave velocity

Face-1 -- Face is perpendicular to the compaction direction.

Face-2 & 3 -- Faces are parallel to the compaction direction.

The total number of specimens tested is three (3) for measuring P-/S-wave velocities. The mean P-wave velocity of each face yields a different value such as 13,910 ft/s, 14,560 ft/s, and 14,380 ft/s for Face-1, -2, and -3. Face-1 stands for the ultrasonic wave direction perpendicular to the compaction direction, whereas Face-2 and Face-3 stand for the ultrasonic wave direction parallel to the compaction directions, respectively.

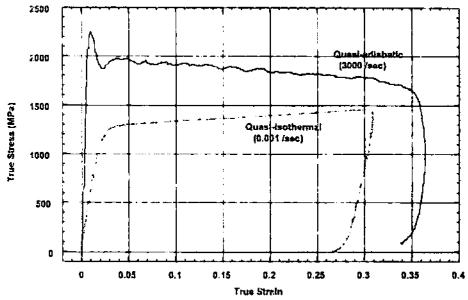

Fig. 4. Stress-strain curves for W-Ti alloy showing strain hardening and flow stress dependence on strain rate.

Typical stress-strain curves of quasi-isothermal and quasi-adiabatic tests are shown in Fig. 4. The curves show an increase in flow stress for the isothermal compression and a decrease in flow stress for high-strain-rate compression. The post-yielding difference between quasi-static and dynamic tests suggests that plastic work be converted into the local heat during excessive plastic deformation. This localized adiabatic heat increases the local temperature, and results in decreasing the post-yielding stress of the W-Ti materials.

6. FUTURE WORK

It is also reported that the strain rate effects of metals are present in metal powder compaction process.[3] This possibility will be investigated by compacting W-Ti powder by means of either quasi-static (Instron machine) or dynamic (SHPB and an accelerated plate impact) method.[8]

The surface temperature variation of the sample will be measured using a high speed indium-antimonide infrared detector (INFR) during dynamic loading in the split Hopkinson pressure bar (SHPB).[6]

The scanning electron microscope (SEM) will be used to examine a relative compactibility, particle deformation during compaction, intra- and/or intergranular fractures of particle-to-particle. Examination of these microscopic observation should provide insight into how explosive affects the metal powder compaction.[7]

Finally, it has been suggested that metal compaction may be strain rate dependent. This possibility will be investigated by preparing W-Ti alloy under various static and dynamic loading condition.

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