IMPACT AND PENETRATION PERFORMANCE OF A TUNGSTEN WIRE/TITANIUM COMPOSITE MATERIAL

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This paper describes a programme of work to manufacture and test a wire-based composite penetrator. A Ti-6Al-4V matrix material is applied to the wire by physical vapour deposition and the material is then consolidated by hot isostatic pressing. Good consolidation of the experimental material was achieved and very high axial strength followed by rapid collapse after a limited strain was observed in laboratory tests. However, although the observed behaviour was similar to adiabatic shear, the microscopic failure was due to fracture of the composite and no shear localisation was detected in the fractured samples. In ballistic trials the material displayed similar density-corrected penetration performance to conventional tungsten heavy alloys but a number of differences in behaviour were observed.

INTRODUCTION

Conventional tungsten heavy alloys (WHAs) for kinetic energy projectiles are manufactured by liquid phase sintering of elemental powders. This places constraints on the structures that can be produced and is not suited to a wide range of potential alloying additions. Several projectiles based on wire have previously been investigated using a range of manufacturing methods [1-3] with the objectives of producing axially aligned properties and/or adiabatic shear failure. For the programme of work described in this paper a titanium alloy was selected as the matrix material because of its well-characterised adiabatic shear tendencies and its excellent ability to flow and bond during hot isostatic pressing (HIPping). The programme takes advantage of equipment and techniques developed for coating titanium alloys onto fibres for commercial applications. The potential benefits of early adiabatic shearing in a penetrator have been widely discussed [4] and much work has been carried out in an attempt to reproduce the adiabatic shearing behaviour of Depleted Uranium (DU) alloys in other materials.

MATERIAL PRODUCTION

The composite material was manufactured by physical vapour deposition (PVD) of a Ti-6Al-4V coating onto tungsten wire followed by a HIP treatment. Commercial drawn tungsten wire of 250µm diameter was selected as having an acceptable balance between fineness and robustness as well as being ideally suited to the standard diameter range of the coating apparatus. Nominal coating thicknesses of 30, 20, and 15µm were manufactured using a Ti-6Al-4V coating. Approximately 1km lengths of wire were coated under vacuum from an electron-beam melted Ti-6Al-4V source during multiple passes within the evaporation chamber. Ultimate coating diameter was controlled by beam power, rate of travel and number of passes. In addition a nominal 30µm coating was applied by co-depositing commercially pure Titanium and pure Tungsten from two separate electrodes in order to increase the density of the matrix material. Following coating the wire was wound onto a large diameter drum with a binding agent and sliced axially to form a sheet. The sheet was then cut into suitably sized strips to be layered into the HIP can with a cavity size of 10x10x110mm (Figure 1). The assembly was then vacuum degassed and sealed by electron beam welding prior to undergoing a standard HIP treatment. Preliminary samples were also produced by pressing wires directly into a cylindrical HIP can.

Figure 1; HIP block, piston, layer of wire preform

The larger blocks all HIPped successfully to a generally uniform structure, normally containing a number of dislocation-like features (Figure 2). In all cases cracks were visible running around the block within the outermost set of wires. Specimens for ballistic and mechanical tests were machined from the blocks by spark erosion.

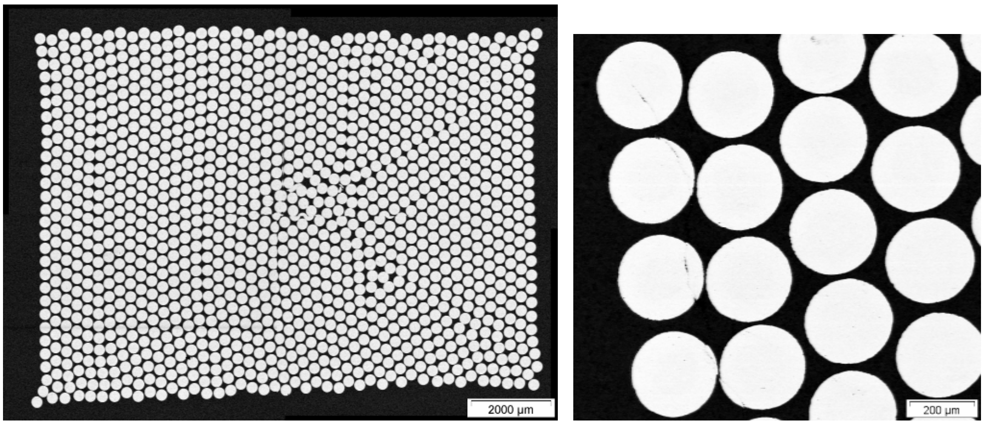


Figure 2; General view of HIPped block + detail of surface cracking

ANALYSIS OF MATERIAL

Scanning Electron Microscope (SEM) examination combined with Electron Back Scattered Diffraction (EBSD) analysis of the wire structure showed it to contain the expected highly elongated grains and to have a dominant <110> fibre texture in the drawing direction. This orientation has been shown, in experiments with single and oriented crystals, to be poor in terms of penetration performance [5-6] and it is unlikely that an alternative wire-drawing operation would produce the more favourable cube ({001}.<100>) texture.

The coating operation produced well-adhered material with expected surface roughness and some layering from the multi-pass deposition visible in the cross-section (Figure 3). This segregation was eliminated by heat-treatment at the HIP temperature.

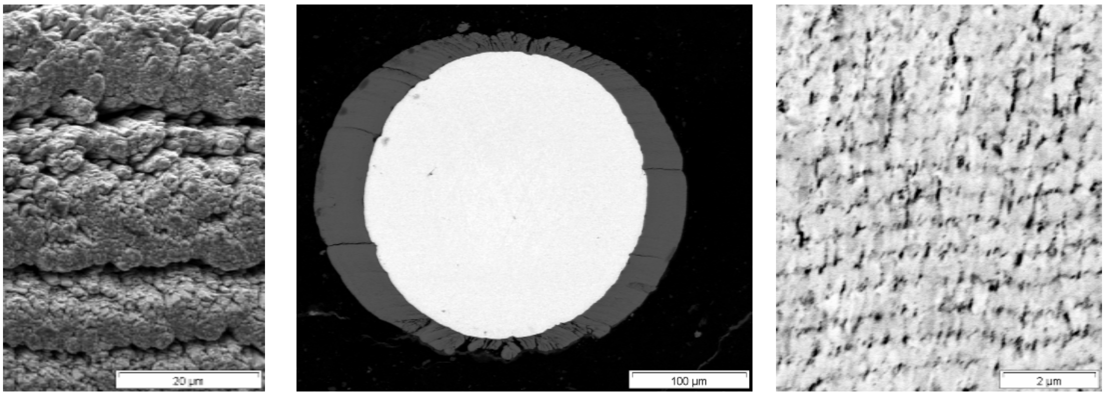
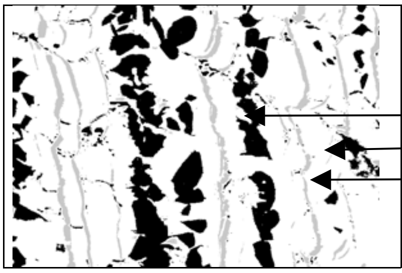


Figure 3; exterior and cross-section of Ti-6Al-4V coated wire (30µm)

In all cases the Ti-6Al-4V coatings were elliptical in form, reflecting the orientation of the wire in the deposition chamber, with no obvious voids but generally containing a number of cracks. In contrast the co-deposited Ti-W coatings were heavily offset relative to the wire and contained significant segregation in the coating which was not removed by heat-treatment or HIPping. Analysis of the coating showed that some areas were formed correctly of a mixture of elements but other layers were dominated by either Ti or W (Figure 4).



Colour	Area fraction	Elemental composition wt%	
		Ti	W
Black	20.15	96.16	3.84
White	68.6	60.90	39.10
Grey	6.5	15.69	84.31

Figure 4; Analysis of W/Ti coating

The structures of the preliminary cylindrical samples exhibited some porosity due to incomplete packing of the can but were otherwise well-formed. One sample was subjected to an extended treatment at the HIP temperature which resulted in formation of a considerable amount of β-titanium alloy in the matrix on the surfaces of the wires due to dissolution of the tungsten (Figure 5a). Later specimens were subjected to the standard HIP treatment only and exhibited only small amounts of β-titanium at the tungsten boundaries.

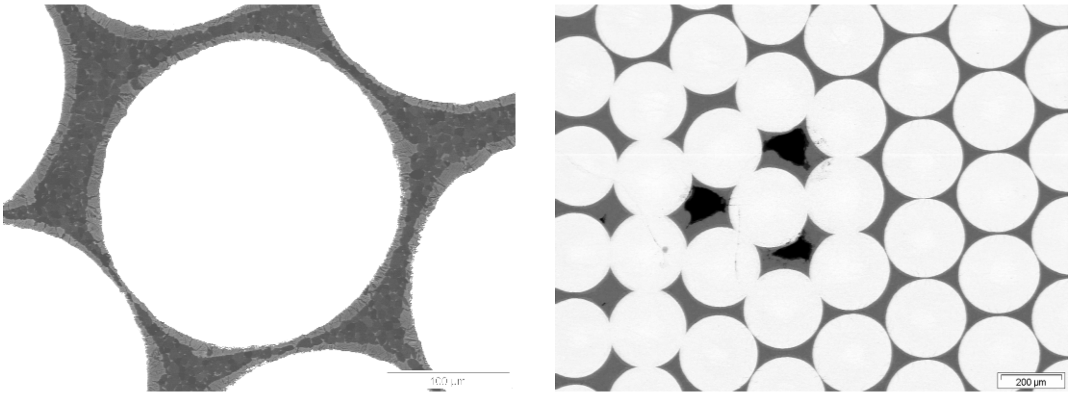


Figure 5; a) initial test specimen with beta phase, b) 15µm coating with voids and contact

The 15µm coating thickness was selected as being close to the theoretical limit for filling the spaces within a fully packed array of wires. In practice a number of voids remained within the blocks after HIPping and, although some areas contained well-separated wires, the wires were in close contact throughout much of the specimens causing additional cracking in the wires from the contact points (Figure 5b).

The material specimens produced had a noticeably higher wire volume fraction than anticipated reflecting the level of porosity and cracking in the coating and explaining the level of porosity in Figure 5b. Details of the wire batches and resultant composite blocks are shown in Table I.

TABLE I: Details of specimens produced

Coating thickness (μm)	Estimated volume fraction of wire (%)	Measured volume fraction of wire (%)	Calculated density (kg/m^3)
30	65	68.8	14.6
20	74	80.6	16.4
15	80	85.7	17.1

Dynamic and quasi-static compression tests were carried out on disc samples cut from the assembled blocks. The material can be seen to have a high dynamic strength and to deform and collapse in a manner superficially similar to DU (Figure 6). Sections cut from tested specimens also showed apparently discontinuous deformation (Figure 7).

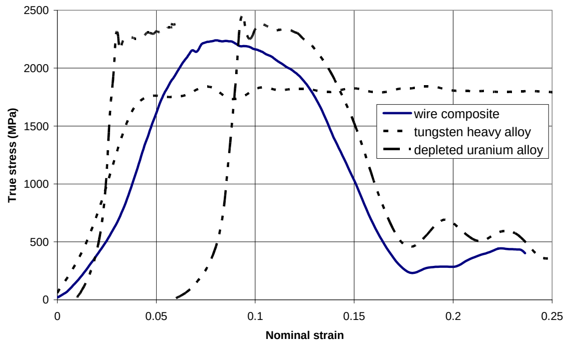


Figure 6; Hopkinson bar compression test results

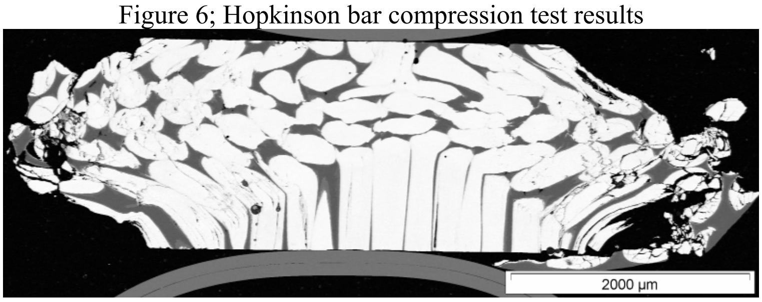


Figure 7; Cross-section of dynamic compression testpiece

This observed structure is similar to that obtained from metallic glass matrix composites in which some evidence of adiabatic shear banding was observed [2]. However, in this case there is no evidence of shear instability and analysis of the fractured specimens shows, instead, straightforward fracture planes running through both matrix and wires with a typical appearance shown in Figure 8.

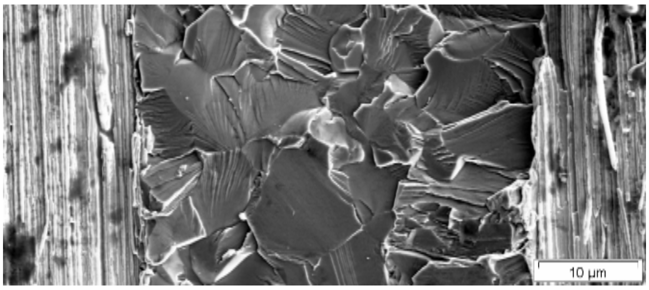


Figure 8; fracture in composite rod

Thus the apparent unstable collapse has been caused by axial cracks in the composite followed by bulk separation and localised buckling of the damaged material.

BALLISTIC EXPERIMENTS

To obtain terminal ballistic data, a 6 mm diameter by 72 mm long flare stabilised projectile was fired from a 40 mm powder gun using a base-push sabot. Four wire composite projectiles were fired into a semi-infinite block of rolled Homogeneous Armour (RHA) steel to UK specification 95/13-1. An identical projectile made from a commercial 92% WHA was also fired. One wire composite projectile was fired into two 9.5 mm plates (in contact) at an obliquity of 60° to the vertical. Details of the tests are given in Table II.

TABLE II. Experimental data

Impact Velocity (m/s)	Projectile mass (g)	Target	Projectile alloy	Pitch (°) ± 0.25°	Yaw (°) ± 0.25°	L_r	Penetration depth (mm)
1677	37	Semi-infinite	92%WHA	-2.1	-2.2	-	70
1672	30	“	Wire	-0.4	-0.7	-	61
1771	30	“	Wire	1.0	-0.4	-	67
1878	30	“	Wire	0.3	-3.6	-	73
1950	30	“	Wire	1.0	-0.7	-	74.5
1481	30	2 x 9.5mm @60°	Wire	0.3	-2.2	37.5	-

Since the wire composite projectile had a lower density than a conventional 92% tungsten alloy, the performance comparison was made on an impact energy as well as an impact velocity basis. Previous semi-infinite penetration data for 92% WHA 6x72 mm projectiles (mass 36.5g) were used [7]. The comparisons are shown in Figure 9. The semi-infinite results lie below the performance of the standard 92% alloy on an impact velocity basis, but are equivalent to the 92% alloy on an impact energy basis.

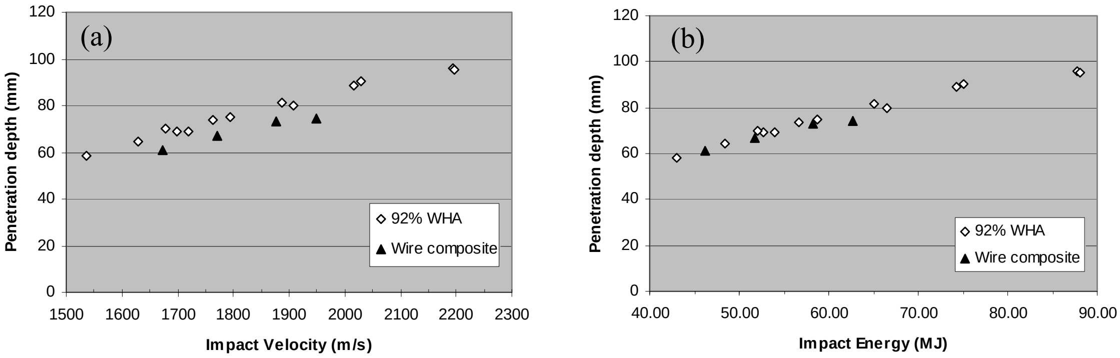


Figure 9. Impact velocity (a) and energy (b) vs. semi-infinite penetration depth

The radiograph from the 1950m/s test against the oblique plate is shown in Figure10. The deformed nose shows an abrupt change in direction rather than the bent 'hooked' shape seen with conventional sintered alloys when perforating an oblique plate. The rear of the projectile has fractured due to the 2° yaw angle. The residual length was 37.5 mm. The nearest comparison to firings of a standard 92% WHA is against a single 20 mm RHA plate at 60° (i.e. 40mm path thickness) where the residual length was between 41 and 41.8 mm from three experiments. Using L_0-L_r/(t cos θ) as the amount of projectile erosion per line of sight thickness, shows a higher erosion rate for the wire composite rod (0.91 compared to 0.76).

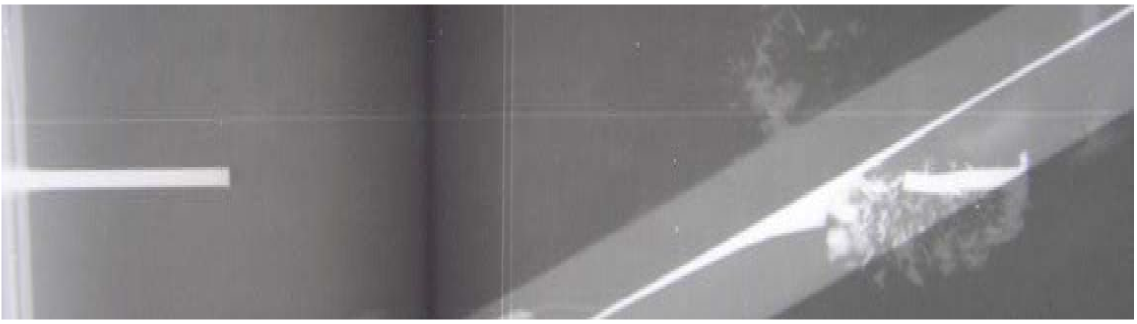


Figure 10. Radiograph from 1950m/s shot showing pre and post impact

SUMMARY

A tungsten wire/titanium-6Al-4V composite material has been successfully manufactured by physical vapour deposition and hot isostatic pressing. The material shows good integrity and exhibited very high strength followed by rapid collapse in compression tests. However, no sign of adiabatic shear was detected in these tests and the actual deformation behaviour was controlled by fracture in the fibre and coating. In ballistic tests the material performed similarly to standard alloys allowing for the lower density but some characteristics of the behaviour were significantly different. High density may be achieved by use of a co-deposited titanium/tungsten coating.

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