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ON THE CRITICAL THICKNESS OF CERAMIC TO SHATTER WC-Co BULLET CORES

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In this paper, the 7.62 mm × 51 mm FFV round consisting of a tungsten carbide core (1550 HV) and copper gilding jacket was fired at silicon nitride, titanium diboride, tungsten carbide and silicon carbide ceramics. Of particular interest is the thickness of the ceramic required to change the penetration mechanism from that of an intact body to broken body, and finally, to becoming completely fragmented during penetration. There appears to be a correlation between the acoustic impedance of the ceramic and the thickness required to shatter the core. The effect of ceramic hardness is less-marked. The existence of a critical thickness to shatter the core suggests that it is not only the *magnitude* of the shock-stress imparted to the core but the *duration* of the shock-stress that is important in causing shattering of these relatively brittle cores.

INTRODUCTION

There has been considerable research over the years into what properties of a ceramic determine its ballistic performance. However, it has become clear that from the wealth of data that has been published there is no single parameter that can be used to determine the resistance to penetration by a projectile. Early work by Cline and Wilkins [1] identified strength, elastic impedance and the ability to withstand tensile stresses before fracture as important properties. More recently, James [2] has shown that with polycrystalline alumina there is no correlation between the ballistic performance of the ceramic and its Hugoniot Elastic Limit and spall strength. In this case, ¼ scale tungsten APFSDS rods were fired into a target consisting of three 25 mm tiles of alumina backed by a semi-infinite RHA stack. These latter results illustrate the paradoxical behaviour of ceramics at relatively high loading rates as one would expect that strength would strongly correlate with ballistic performance. For attack by small arms ammunition, other studies have shown that hardness is an important factor and determines the ability of the ceramic to shatter the projectile and thereby reduce its kinetic energy density (see for example [3]). For many steel-cored small arms threats, the hardness of the ceramic will inevitably overmatch the hardness of the core and therefore relatively thin sections of sintered or even reaction-bonded ceramic materials can be adhered to an appropriate backing to provide a weight efficient, cost effective armour solution. However, with the proliferation of tungsten carbide cored ammunition as found in the 14.5 mm × 114 mm BS41 API and the 7.62 mm × 51 mm FFV bullets the thickness and type of ceramic required for an optimised ceramic armour will need to be carefully considered. Thankfully, tungsten carbide possesses a relatively low strain to failure when compared to steel or tungsten alloys. Even relatively tough cermets that contain 15 % cobalt content will have a strain to failure of 0.15 % when loaded in tension [4]. Therefore, if we can shatter the core of the round by using a ceramic then the penetrability will be greatly reduced. This work examines the existence of a critical thickness of ceramic required to shatter these relatively brittle cores.

EXPERIMENTAL

The Depth of Penetration (DoP) technique as described by Rozenberg and Yeshurun [5] was used to measure the ballistic performance of the ceramic tiles. For backing for the DoP experiments, a common engineering aluminium alloy Al 6082 T651 was used (YS = 250 MPa). The test backing were 50.8 × 50.8 mm pieces cut from a single 25 mm thick plate. For each ceramic tile of specific thickness (t_c), a single bullet was fired at the target and the residual penetration (P_r) into the aluminium alloy was measured (see FIGURE 1); at least three experiments were done for each tile thickness.

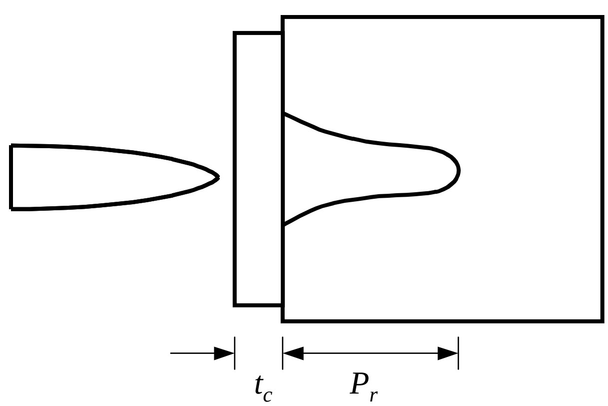

FIGURE 1: THE DOP TECHNIQUE.

Two ceramics manufactured by Ceradyne Inc. were studied: hot-pressed silicon nitride and hot-pressed silicon carbide. In addition, a Morgan AM&T silicon carbide - sintered Purebide™ PS5000 and a Cercom hot-pressed tungsten carbide were considered. Finally, a hot-pressed titanium diboride was studied. The tungsten carbide ceramic is a composite consisting of two distinct materials, namely, WC (97.2% by weight) and W_2C (2.8% by weight) [6]. Some properties of the ceramics are provided below in Table I. The data for the hot-pressed tungsten carbide is derived from data presented in reference [6]. Apart from the hot-pressed silicon carbide, hardness values were measured using an Indentec HWDM7 Digital Micro Hardness Machine by taking the average of five measurements.

For each case, the thickness of the ceramic tile was increased nominally by 1 mm until the WC-Co core had shattered. We defined the core being in a 'shattered state' when no discernable shank of the core was visible from the x-rays. When some part of the shank of the core was visible from the x-rays, the state was defined as 'broken body' and 'intact' when no fracture or fragmentation was evident apart from an occasional spall crack. A nominal thickness of 1 mm indicates the uncertainty that that we have with the results. However, in some cases, this uncertainty was reduced by reducing the incremental increase in the thickness.

Each ceramic tile was glued to the aluminium alloy backing block using Araldite 2015. This was applied to the mating surfaces and then the ceramic and aluminium block were pushed together and twisted / oscillated until an even thin adhesive line had been achieved with no gaps or obvious air inclusions. This was done to achieve a consistent contact between the ceramic and the aluminium for all samples tested.

The range set up was one of a fixed test barrel mounted ten metres from the target. Bullet velocity was measured using the normal sight-screen arrangement. The test ammunition was 7.62 mm × 51 mm NATO FFV ammunition was used as factory loaded and generated a mean velocity of 973 m/s. The bullet core consists of tungsten carbide core (composition by percentage weight C 5.2, W 82.6, Co 10.5, Fe 0.41 [7]) of hardness 1550 [HV0.3], mounted in a low carbon steel jacket with gilding metal, on an aluminium cup.

TABLE I: MECHANICAL PROPERTIES OF THE CERAMICS USED; THE WC-CO CORE MATERIAL OF THE BULLET IS PROVIDED FOR COMPARISON.

Ceramic	Density (kg/m^3)	E (GPa)	$\sqrt{(\rho E)}$ ($MPam^{-1}s$)	Hardness, HV (kg/mm^2)
HP Si3N4	3100	310	31.0	1793 [2.0]
HP SiC	3150	400	35.5	2300 [0.3]*
Sintered SiC	3140	413	36.0	2782 [2.0]
HP TiB2	4480	555	49.9	2226 [2.0]
HP WC	15560	689	103.5	2297 [2.0]
WC-Co core	14813	630	97.0	1550 [0.3]

* Hardness value from manufacturer's data.

The test jig was firmly clamped to a test fixture adjustable for height and lateral position and axially aligned with the direction of shot. The jig position was accurately adjusted to ensure that the centre of the target block corresponded with the centre of the shot-line; the jig used engineering vee-blocks as clamping elements (see FIGURE 2). Each of the samples was clamped in place in turn with the ceramic sample protruding out of the front of the clamps. Behind the sample, in the vee-blocks, were three more of the 25-mm blocks of aluminium alloy giving a possible total DoP of 100 mm – effectively semi infinite for the purposes of the test ammunition.

After testing the aluminium alloy blocks were x-rayed which allowed the residual penetration to be accurately measured. Furthermore the level of fragmentation of the core and the overall shape of the penetration crater was assessed from the x-rays. Where uncertainty existed on the state of the core it was examined after sectioning the targets.

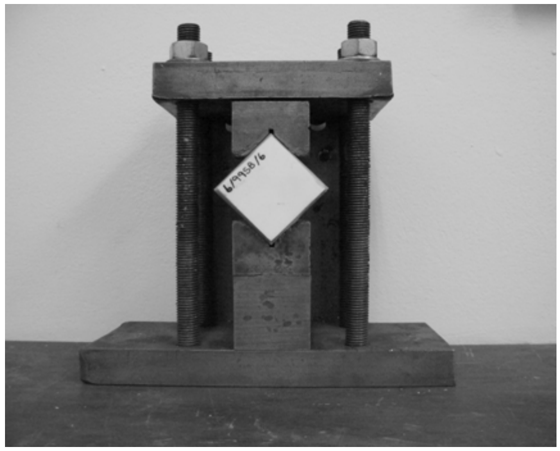

FIGURE 2: TEST JIG WITH CERAMIC-FACED ALUMINIUM ALLOY PLATE IN PLACE.

RESULTS

In all, five different ceramics were tested with an average of three separate thickness and three shots per thickness of ceramic. Despite the relatively small lateral dimensions of the ceramic to each thickness, the scatter of the depth of penetration results was relatively small. The nominal thicknesses of ceramic required to cause 'broken-body' penetration and shatter the core are tabulated in TABLE II; the values of thickness and mean penetration depth into the aluminium alloy ± 1 standard deviation are presented.

TABLE II: CERAMIC THICKNESS AND RESIDUAL PENETRATION FOR THE BROKEN AND SHATTERED CORE.

		Core = broken body		Core = shattered	
Ceramic	$\sqrt{(\rho E)}$ ($MPam^{-1}s$)	t_{c1} (mm)	$P_r \pm \sigma$ (mm)	t_{c2} (mm)	$P_r \pm \sigma$ (mm)
HP Si3N4	31.0	6.5	27±0	7.6	14.7±5.3
HP SiC	35.5	5.5	26.5±4.3	6.5	8.2±2.0
Sintered SiC	36.0	4.3	33.3±1.3	5.8	9.5±1.0
HP TiB2	49.9	3.9	26.5±0.4	5.4	15.2±1.8
HP WC	103.5	2.6	33.3±1.3	3.6	19.2±2.9

For the hot-pressed silicon nitride, extensive fragmentation of the core had occurred with 7.54 mm of ceramic whilst with 6.51 mm thick ceramic showed that the core was able to penetrate the aluminium alloy to a depth of 27 mm whilst maintaining its initial shape. With 5.45 mm of hot-pressed silicon carbide the penetrator was able to penetrate into the aluminium alloy a distance of 26.5 mm.

Increasing the thickness to 6.53 mm reduced the penetration depth to an average of 8.2 mm with the core being shattered and irrecoverable. The sintered silicon carbide appeared to fracture the core with a relatively thin section of ceramic. With 4.86 mm of silicon carbide in place, the penetration into the aluminum alloy had been reduced to 16.7 mm and the core appeared to be partly fragmented indicating a change in the penetration mechanism during penetration of the aluminum alloy (see FIGURE 3 below). The onset of complete fragmentation for this ceramic occurred within the thickness range 4.3 – 5.8 mm.

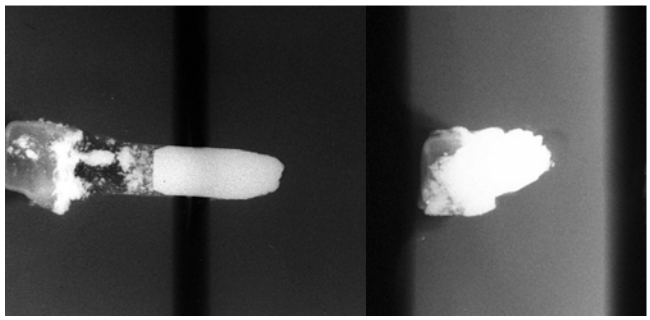

FIGURE 3: X-RAY OF THE FFV CORE AFTER COMPLETELY PENETRATING 4.3 MM OF SINTERED SILICON CARBIDE (LEFT) AND 4.86 MM (RIGHT).

For the titanium diboride it was quite difficult to establish a critical thickness that would be required to shatter the core as extensive fracturing appeared with thickness values as low as 3.95 mm. However, with 4.84 mm the core was partly fragmented (see FIGURE 4) and fully fragmented with 5.4 mm of ceramic. Finally, the hot-pressed tungsten carbide ceramic was able to shatter the core with 3.60 mm of ceramic in place. This is despite ~1.5 mm of tungsten carbide appearing to have little or no effect on the core. A thickness of 2.57 mm of tungsten carbide was able to break the core.

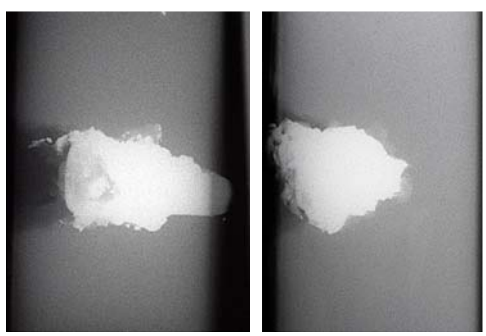

FIGURE 4: X-RAY OF THE FFV CORE AFTER COMPLETELY PENETRATING 3.95 MM OF HOT-PRESSED TITANIUM DIBORIDE (LEFT) AND 4.84 MM (RIGHT).

DISCUSSION

Below is a graph (FIGURE 5) showing the thickness of ceramic required to shatter the WC-Co core of the FFV round. The individual data points are calculated from TABLE II by averaging t_{c1} and t_{c2} as the critical thickness required to fragment the core must lie between these two limits (indicated by the error bars). A linear trend-line is fitted through the data. Increasing the relative impedance of the projectile and the target results in an increase in the thickness of the ceramic required to shatter the core. This is consistent with earlier observations [1].

The reason for this apparent correlation in FIGURE 5 can be partly explained in terms of the shock stress delivered to the projectile and target on impact. For a 1D uniaxial strain impact the magnitude of the shock stress can be calculated from the well known relationship

$$\sigma = \frac{Z_1 Z_2}{Z_1 + Z_2} u_0 \tag{1}$$

where Z_1 and Z_2 are the impedances of the projectile and target respectively and u_0 is the impact velocity of the projectile, σ is the shock stress at impact. This assumes a linear σ - u Hugoniot curve for both projectile and target. Therefore, increasing the acoustic impedance of the target increases the shock stress in the projectile core.

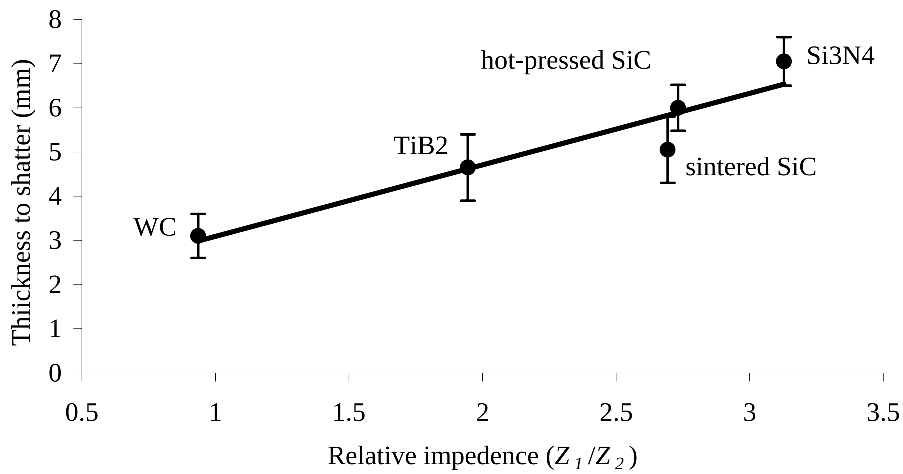

FIGURE 5: THICKNESS OF CERAMIC REQUIRED TO SHATTER THE WC-CO CORE FROM THE 7.62 MM X 51 MM FFV ROUND.

Interestingly, for all of the ceramics tested there was a minimum thickness where the impact appeared to have no visible effect on the core and therefore it was able to penetrate in a rigid-body manner. The existence of a critical thickness to shatter the core suggests that it is not only the *magnitude* of the shock-stress imparted to the core but the *duration* of the shock-stress that is important to cause shattering of these relatively brittle cores. The accumulation of damage ahead of the penetrator will also affect the duration of the wave in the core and suggests that a slower rate of damage accumulation will lead to a lower critical thickness under these loading conditions. The sintered silicon carbide appeared to perform slightly better than the hot-pressed silicon carbide (with less thickness required to induce fracture). However, hot-pressed silicon carbides tend to possess relatively high resistance to damage accumulation compared to sintered silicon carbides. For example, Pickup and Barker [8] studied two ceramics that had been subjected to 1D uniaxial stress experiments at strain rates ranging from 10^{-3} /s to 10^{3} /s. One ceramic was

Cercom's SiC B, a hot-pressed ceramic, and the other was SiC 100, a pressureless sintered ceramic manufactured by Wacker-Chemie. In these experiments they measured the time to failure. They noted that the time to failure of the SiC B was 50 % higher than that of the SiC 100 and suggested this could be explained by the microstructure. The main difference was that transgranular cleavage had occurred in the SiC 100 and intergranular failure had occurred in the SiC B. After comminution (that is, the reduction of intact ceramic to small fragments), the SiC B consisted of particles of closely interlocked grains. This could provide considerable resistance to deviatoric stresses. If the grains cleave and co-operative movement is enabled, the shear strength is reduced. Similar failure mechanisms have been reported by Woolmore *et al* [9] when a hot-pressed silicon carbide (again, Cercom's SiC B) and the sintered silicon carbide used in these trials were loaded ballistically by the 14.5 mm × 114 mm BS41 API round. However, it is unclear whether these observations correlate with the behaviour of the hot-pressed silicon carbide used in this study.

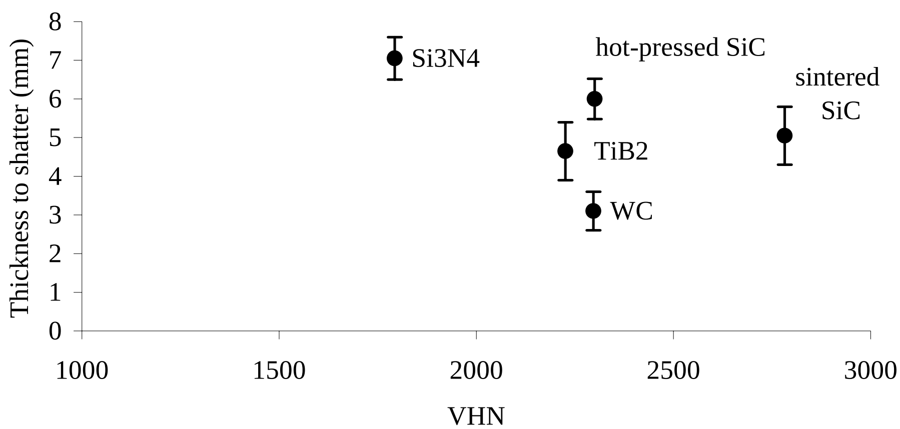

FIGURE 6: THICKNESS OF CERAMIC REQUIRED TO SHATTER THE WC-CO CORE FROM THE 7.62 MM X 51 MM FFV ROUND AS A FUNCTION OF THE CERAMIC'S HARDNESS.

There appears to be a less-marked correlation of the hardness of each of the ceramics and the critical thickness required to shatter the WC-Co core with the impedance of the ceramic as shown in FIGURE 6. Nevertheless, the two properties (impedence and hardness) must both play a role in defeating the core. It should be noted that the hardness of the ceramics is notoriously difficult to measure. However it is thought that the hardness of inter-locked comminuted ceramic ahead of the penetrator plays a role in its flow and therefore is important in resisting penetration of the core – whether it is intact, broken or fragmented.

CONCLUSIONS

There appears to be a correlation between the acoustic impedance of the ceramic and the thickness required to shatter the WC-Co core. There is a less-marked correlation on the hardness of the ceramic on this phenomenon. The existence of a critical thickness to shatter the core suggests that it is not only the *magnitude* of the shock-stress imparted to the core but the *duration* of the shock-stress that is important in causing shattering of these relatively brittle cores.

Of course, the thickness required to shatter the core is not the whole story and it should be noted that this observation will probably only hold for relatively brittle cores made from tungsten carbide cermets. Certain ceramics retain the ability to pressure harden, pressure soften and retain significant strength after being fragmented themselves and it is probable that this latter occurrence is a function of the hardness of the ceramic and the strength of the interlocking comminuted particles.

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