

Ballistic testing of armour grade ceramics

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Armour grade ceramic materials are used in ceramic based armour systems in vehicles and body armour. Ceramic based armour provides light-weight solutions against a range of threats, including armour piercing bullets. Generally, the ceramic is supported by a backing material that typically is a fibre composite (like aramid or UHMW-PE) or a metal. The function of the ceramic is to erode the core of the AP round and to distribute the dynamic loading over a wider area of the backing material. The function of the backing material is to prevent fragments (ceramic or projectile) to penetrate and absorb the (remaining) kinetic energy of the system. The ballistic efficiency of a ceramic based armour highly depends on the performance of its ceramic component. Using the Residual Energy Method (REM) on bare ceramic tiles, the efficiency of the ceramic to erode and decelerate the AP core can be determined. Using a bare tile allows a pure ceramic-projectile interaction, which can be very reproducibly tested. In the test the mass and velocity of the residual AP core are measured, hence the loss in kinetic energy of the core is known. Also, the diameter of the first axially responding part of the rear of the tile is determined (from high-speed video recording), which provides information about the cone-crack angle. Using several ceramic tiles that have the same areal density ($AD = \rho * t$) their ballistic efficiency can be determined and used to rank them. Examples are provided of REM results obtained with (armour grade) SiC tiles of various suppliers.

1. INTRODUCTION

The lightest personal and vehicle armour systems make use of (armour grade) ceramic materials, like Al_2O_3 (alumina), SiC (silicon carbide) and B_4C (Boron carbide). Production of armour grade ceramic materials like SiC and B_4C has largely been extracted from Europe. This leads to a dependency of other countries which can suffer from long lead times and high prices.

To explore alternative sources for these important armour components, TNO was asked to perform ballistic tests on SiC tiles of various suppliers. This provides an insight in the ballistic protection capability of such ceramic components.

Many efforts have been made to rank armour ceramic tiles using the Depth-of-Penetration (DoP) method [1]. Here, the tile is adhesively bonded to a semi-infinite backing material (like an aluminium alloy block) and shot using an armour piercing bullet. The depth of penetration in the backing material is used by many researchers to rank various ceramic tiles. However, this DoP method has serious drawbacks such as the semi-infinite backing which is not representative of realistic armour concepts and the large variation in test results [2]. The latter can be compensated by performing a large number of repeated experiments, however this is seldom done.

Using the Residual Energy Method (REM) the reduction in kinetic energy of the core of an armour piercing (AP) bullet can be determined. This method allows the ballistic efficiency (BE) to be determined for any target (material or armour system), including the bare SiC tiles used here. The testing of bare ceramic tiles provides a very reproducible target-bullet interaction, as the influence of a backing material, adhesive layer and internal stresses as well as confinement are excluded.

The ballistic efficiency expresses the relative reduction in kinetic energy of the AP core (as a percentage). In this paper the REM is used to compare SiC tiles of various suppliers and explore if there are any correlations with their material properties.

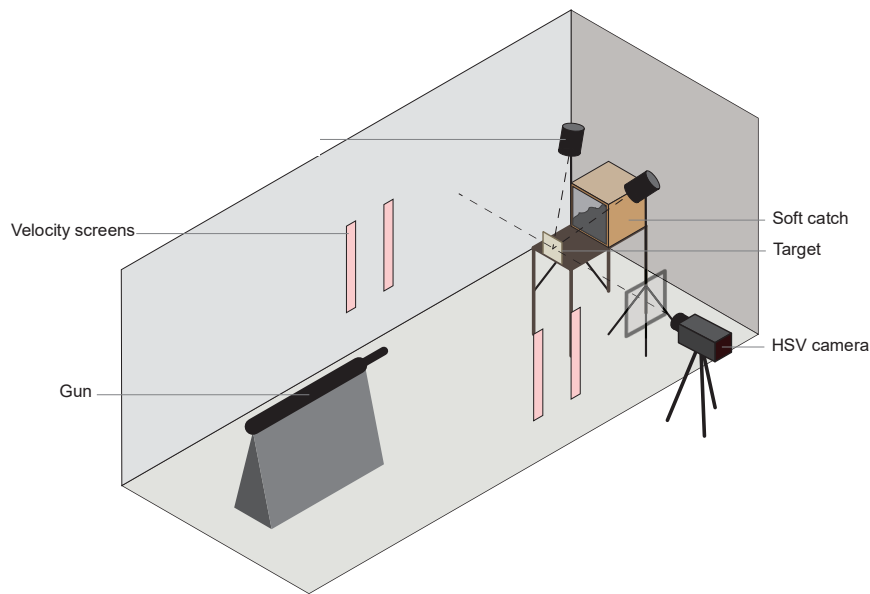


Figure 1. Test setup for the combined test method REM.

2. RESIDUAL ENERGY METHOD

Figure 1 shows a typical test setup for the REM. The projectile is fired using the appropriate gun and propellant. The infrared velocity screens allow the determination of the speed of the incoming projectile. The ceramic tile is positioned perpendicular to the line of fire on a steel platform, a small amount of ballistic clay is used in between in order to avoid the tile from dropping before the shot is fired. A high-speed video camera captures the interaction of the projectile with the target. By analysing the high-speed images, both the impact velocity of the projectile and the residual velocity of the projectile/fragment cloud can be determined. It is assumed that the velocity of the residual AP core is equal to that of the tip of the fragment cloud. Experimental support for this assumption was obtained from flash X-ray images, as well as high speed video recordings of a fragment cloud after passing a gap between two steel plates (positioned 10 cm behind the ceramic tile) that showed both the bullet and the (now 2-dimensional) fragment cloud. Both recording methods, as well as simulations [3] showed that residual projectile parts have a similar velocity (at that position) as the tip of the fragment cloud.

The soft catch (residual projectile catching device) is able to decelerate the residual projectile or fragments without any plastic deformation, allowing the retrieval of the eroded residual projectile or its core fragments.

The REM ballistic testing method more specifically determines the degree of erosion and deceleration of the projectile after target interaction.

A scenario where an AP bullet interacts with an armour grade ceramic tile is schematically shown in Figure 3. Using a very high frame rate (order of 10^5 fps) with the high-speed camera, behaviour of the material can be observed such as bullet deceleration and cone formation in the tile. The dimension of the cone base ($2R$) is observable, from which the cone angle (α) can be calculated using the tile thickness and projectile core diameter [2].

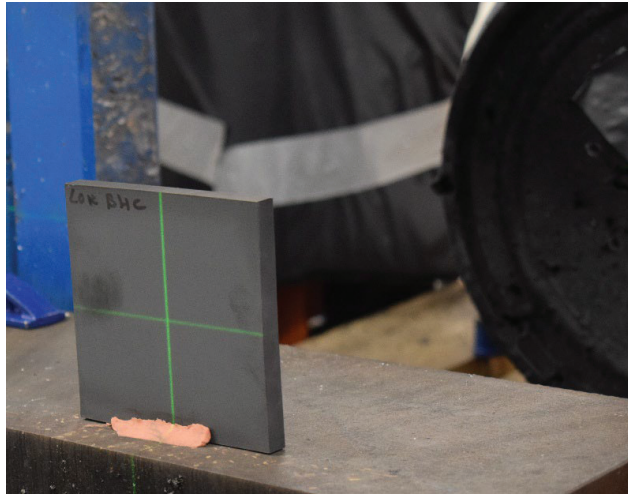


Figure 2. Photograph of a ceramic tile on the platform in front of the soft catcher.

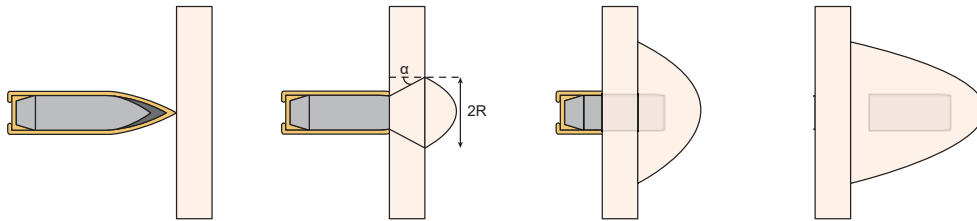


Figure 3. Schematic view of high-speed video images at various interaction times.

Based on the masses and velocities of the AP core before and after impact on the ceramic tiles the kinetic energy loss ΔE_{kin} of the AP core can be calculated:

$$\Delta E_{kin} = 0.5 * m_{core} * v_0^2 - 0.5 * m_{core,residual} * v_{cloud}^2 \quad (1)$$

Where m_{core} is the initial AP core mass and v_0^2 the square of the impact velocity.

The material or armour system can be ranked using the fraction of energy loss of the AP core they provide.

$$Ballistic\ efficiency = \frac{\Delta E_{kin}}{E_{kin,0}} \quad (2)$$

Where $E_{kin,0}$ is the kinetic energy of the AP core before impact.

As the REM uses mass and velocity of the bullet/core before and after penetration, it can be applied to any armour system (a single plate or a complete armour system), as long as the target is overmatched by the projectile. In this work the tiles have been shot using an armour piercing rifle bullet (7.62 mm AP) that strikes the bare SiC tile at a velocity of 825 m/s in the center of the tile at normal impact condition.

Table 1. Overview of SiC samples and some of their properties

Sample	Density	Thickness	Areal	Longitudinal	Transversal	Youngs	Shear	Compression	Poisson's	Vickers
	[g/ccm]	[mm]	Density [kg/m ²]	Sound velocity [km/s]	Sound velocity [km/s]	Modulus [GPa]	Modulus [GPa]	Modulus [GPa]	ratio [-]	HV1 [GPa]
A	3,154	8,05	25,4	12,00	7,80	435	192	198	0,13	25,1
B	3,134	8,03	25,2	11,80	7,53	411	178	199	0,16	23,6
C	3,156	7,89	24,9	11,24	7,56	392	180	158	0,09	23,6
D	3,155	8,10	25,6	11,70	7,20	391	164	214	0,20	21,7
E	3,134	9,08	28,5	11,83	7,56	414	179	200	0,15	22,9
F	3,144	7,26	22,8	11,65	7,50	405	177	191	0,15	22,8
G	3,097	7,70	23,8	11,23	7,43	380	171	163	0,11	22,2
H	3,152	7,95	25,1	11,99	7,54	420	179	214	0,17	22,7

3. MATERIALS

Several suppliers of armour grade siliconcarbide (SiC) material have been requested to send samples free of charge. We have received samples from several countries, including China, USA, Italy, and South Korea. The squared SiC tiles that were supplied should ideally have dimensions of 100x100x8 mm. Table 1 shows an overview of the samples and some of their mechanical properties. The actual tile thicknesses vary between 7.26 and 9.1 mm. The density of the samples was measured using He-pycnometry, while the longitudinal and transversal sound velocity were measured using ultrasonic equipment (at 5 MHz). From the density and sound velocities, the elastic moduli (E, G and K as well as the Poisson's ratio) have been calculated. The Vickers hardness was obtained using a micro-Vickers hardness indenter with an indentation load of 10N.

The hardness values of all SiC samples ranged between 21.7 and 25.1 GPa. Such high hardnesses are considered sufficient for the erosion of AP core materials. The material properties provided in Table 1 allow to explore possible correlations. Although the range in moduli seems limited, in Figure 4 a linear correlation between the elastic moduli (E, and especially G) and the Vickers hardness of the samples is shown. This can have practical applications, as the sound velocity and density of a tile can be measured before a ballistic experiment, and it does not change/damage the material. Hence, it is rather easy to determine the elastic modulus of a material and estimate its hardness through the linear correlation in Figure 4. To measure the hardness of a ceramic material directly, a very small piece/fragment needs to be embedded, grinded and polished before the hardness indentation can be made.

Sample G has a relatively low density of 3.097 g/cm³ and it also shows the lowest elastic modulus and hardness of all samples. Although not investigated in this study, this sample may have some porosity which is generally considered to be detrimental to the mechanical properties of a ceramic.

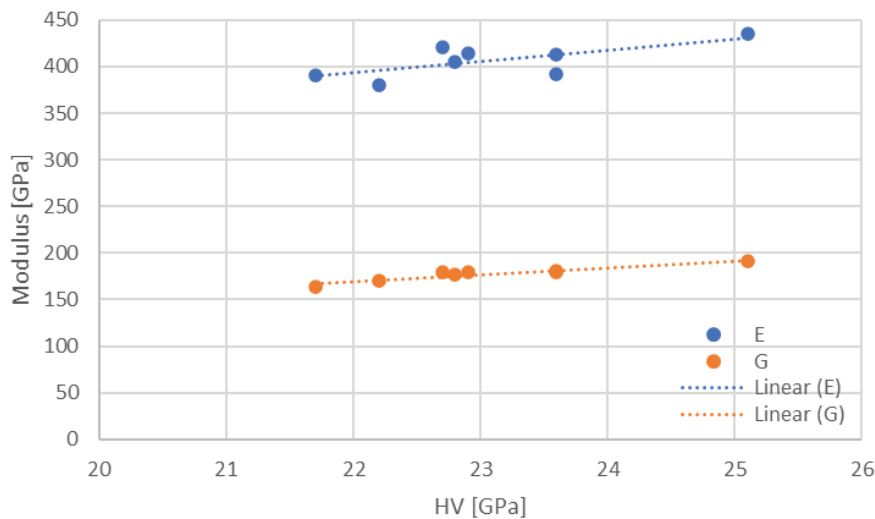


Figure 4. Calculated elastic moduli (E, G) versus the Vickers hardness of the SiC samples

4. TEST RESULTS

Table 2 shows the average of 3-10 (typically 4) repeated shots on the SiC samples. The column ‘BE’ shows the (average) ballistic efficiency (BE) of the tiles. There are some differences in tile thickness, hence areal densities (AD) between the samples. When the AD differs too much, this prevents a direct comparison between these materials. To compensate for these differences, the BE-values have been divided by their AD and multiplied by 25 kg/m². This results in a linearly AD-corrected BE, which allows the samples to be compared and ranked more effectively. The results of this AD-correction of BE (‘BE eff’) is shown in the last column of Table 2.

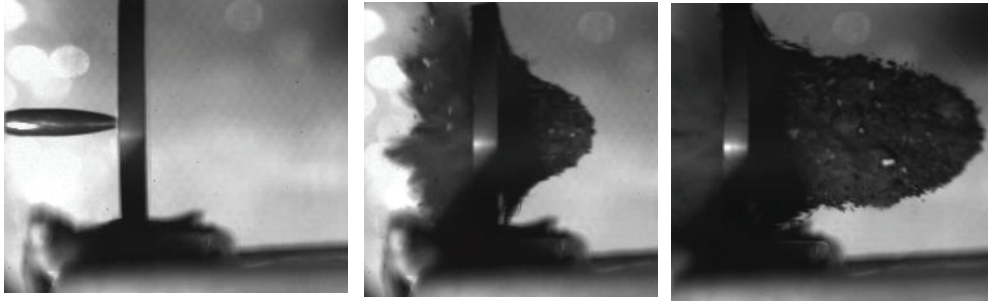


Figure 5. High speed video stills showing bullet just before and after impacting a bare ceramic tile

Table 2. Overview of REM test results for bare B₄C tiles

Sample	AD [kg/m ²]	Vo [m/s]	Vr [m/s]	mr [gram]	Ekin,0 [J]	Eres. [J]	ΔE [J]	BE	BE eff
A	25,4	827	591	2,33	1279	406	873	68%	67%
B	25,2	826	613	2,63	1276	494	782	61%	61%
C	24,9	825	616	2,79	1273	529	743	58%	59%
D	25,6	825	597	2,60	1273	463	809	64%	62%
E	28,5	825	578	2,41	1273	403	870	68%	60%
F	22,8	825	658	2,95	1273	639	634	50%	55%
G	23,8	823	623	2,83	1267	549	717	57%	59%
H	25,1	823	579	2,52	1267	422	844	67%	67%

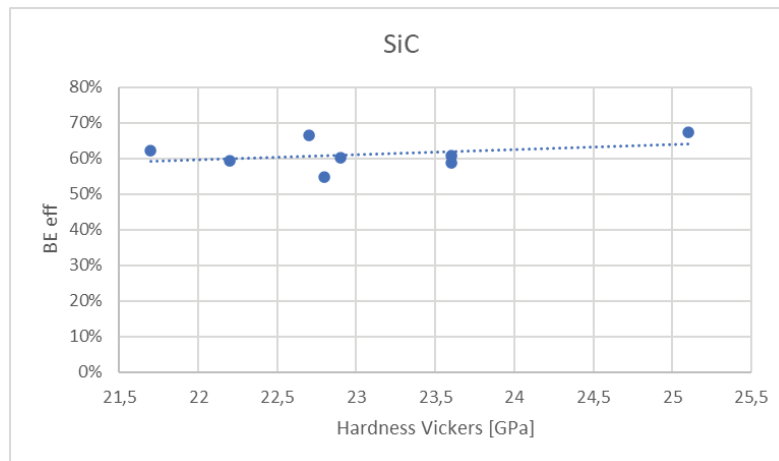


Figure 6. Graph showing the effective ballistic efficiency of the SiC tiles.

5. DISCUSSION

It may feel strange to test ceramic tiles in their bare state. However, the fracturing processes in ceramic (with extreme high sound velocities) are not different when the tile is backed by a material or not. The local bullet impact results in a cone-crack (strike-face to the rear of the tile) under an semi-cone angle that is defined by both intrinsic and extrinsic tile parameters (like strength and thickness). The impulse of the local impact causes the tile to bend bi-axially, which leads to high tensile stress at the rear of the tile (due to its thickness and stiffness). The tensile stress leads to radial cracks and later circumferential cracks, which due to interaction of cracks leads to fragmentation of the tile (and a fragment cloud due to impulse conservation). It is mainly inertia of the ceramic cone that controls the interaction; deceleration and erosion of the AP core as it cannot penetrate the ceramic material. Therefore, it is of high importance to compare ceramic tiles based on an equal areal density. And (second best) to correct for differences in areal density (AD). As was done in this work using AD-compensated effective BE.

The mass of the cone-fragment that is formed needs to be accelerated by the impacting/eroding bullet/core. For a ceramic with a backing material, the same occurs to the ceramic tile (same crack formations), however now the inertia of the cone fragment has increased due to the mass of the backing material (supporting the cone). Thus, the inertia of the ceramic cone fragment has increased a lot, and the bullet will be more eroded and decelerated. The residual kinetic energy of the projectile, cone and backing (part that is in direct contact with the cone fragment) can be absorbed by the strength/toughness of the backing material (plastic deformation, visco-elastic strain, fiber strain, delamination, etc.). This is why a ceramic tile needs a backing material in order to stop a threat. Yet, for the REM we need a residual penetrator, hence the projectile should overmatch the target. This can be done for thin backing materials, and certainly for a bare ceramic tile. The REM test method is energy based and as such can be applied to any target material or armour system. This includes that of otherwise difficult to test armour materials such as ceramic tiles. It can also be used to quantify the effect of damage or aging of complete armour systems. In all cases the REM is used with impact conditions that overmatch the target. The perforation allows the energy of the residual projectile to be determined (together with the status of the residual penetrator; intact, broken, deformed or eroded/shattered). For a fair comparison between different targets, one needs to make sure that all samples involved have similar areal density (hence density times thickness).

Figure 6 shows the BE eff. values of the SiC samples versus their Vickers hardness. The limited range in hardness of these samples does not allow us to draw conclusions about any correlation or trend. The rather close ballistic efficiencies of these samples show that a pure armour grade ceramic material has much less extrinsic properties (like residual porosity) that can influence the mechanical behaviour. Also, the influence of lateral tile dimensions was excluded, as all tiles had the same shape and size (100 x100 mm squares). Performing ballistics tests using the ceramic tile in bare tile state avoids any influence of the backing material and its adhesive bonding. This results in a rather reproducible test and a good average mass and velocity of the residual projectile can be obtained in 3-5 repeated shots. The SiC samples can now be ranked according to their effective BE values; samples A and H show the highest ballistic efficiency (67%), while sample F has the lowest BE eff value (55%). This order is reflected in the Youngs modulus as samples A and H also have the highest values (420 GPa or above).

6. CONCLUSION

Ballistics tests using 7.62 mm AP bullets have been performed on bare SiC tiles of various suppliers. The density, hardness and sound velocities have been determined from which the elastic moduli have been calculated. The Vickers hardness of the samples show a linear correlation with elastic moduli (E and G). This may be used to predict the hardness of a SiC tile, when only its sound velocity is known or measured. The ballistic efficiency (normalized energy loss of the AP core) has been determined for the SiC samples obtained from various suppliers. After correcting for differences in areal density (tile thickness), the samples can be ranked using the effective ballistic efficiency (eff BE). The range in BE efficiency for the tested SiC samples lies between 55% and 67%. The highest eff BE was obtained for the SiC samples that also have the highest Youngs modulus (>420 GPa).

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References

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