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English summary

Protection against high-velocity impact from objects such as projectiles is of major concern for bothmilitary and civilian purposes. Lightweight body armour systems for ballistic protection of personnel can be designed by combining different materials with different properties. These hybrid systems typically have a hard ceramic strike face that blunts, fractures and erodes the projectile, and a soft backing, made from ballistic fibres, that absorbs the residual energy.

FFI has for many years been involved in the development of, and research on, body armour for protection of military personnel. In the period from 2004 to 2007, the technology behind an armour plate was developed in cooperation with industry. For future developments, however, it is necessary to have knowledge about the mechanisms that are acting under ballistic impact. Today, this topic is studied in several projects at FFI, and this report was written as a part of that work.

The most common ceramics for armour purposes are - in order of improved performance - aluminium oxide, silicon carbide and boron carbide. The ceramics generally have relatively low density and high hardness. These, and other properties, make them useful in armour applications. The mechanisms by which a ceramic armour fails is quite complex, and involve failure mechanisms such as radial cracking, cone cracking and comminution due to micro-cracking. To what extent they appear and the relative timing of these mechanisms, depends on factors such as the impact velocity, the ceramic and projectile properties, and the dimensions of the ceramic and projectile.

To improve the ballistic performance of the ceramic armour system, it is desirable to delay the failure of the ceramic for as long as possible. This allows more time for deformation and erosion of the projectile. It has been shown in the literature, and by work conducted at FFI, that the ballistic performance, both in terms of single-hit and multi-hit capacity, can be improved by radially confining the ceramic tile, by covering it with a sheet of another material, and/or by tuning the interfacial strength between the cover and the ceramic.

The main aim of this report is to give an overview of the mechanisms that are involved in ballistic, or dynamic, failure of ceramics and ceramic-based hybrid armour. The failure mechanisms, the factors that govern the failure mechanisms, and what can be done to delay the failure of the ceramic, are discussed on the basis of some of the available literature on the topics.

Sammendrag

Beskyttelse mot anslag fra blant annet prosjektiler ved høy hastighet er et viktig tema innen både militære og sivile anvendelser. Lettvektsløsninger for ballistisk beskyttelse av personell kan designes ved å kombinere ulike materialer med ulike egenskaper. Disse hybridsystemene har typisk en hard plate av keramikk som avrunder, bryter opp og eroderer prosjektilet, samt en myk 'backing' laget av ballistiske fibre som absorberer den gjenværende energien.

FFI har i mange år vært involvert i utvikling av og forskning på ballistisk beskyttelse for militært personell. I perioden 2004 til 2007 ble teknologien bak en beskyttelsesplate for soldater utviklet i samarbeid med norsk industri. For videre utvikling av teknologien er det imidlertid nødvendig med en bedre forståelse av hvilke mekanismer som finner sted ved ballistiske anslag. Dette er et tema som for tiden studeres i flere prosjekter ved FFI, og denne rapporten ble skrevet som en del av dette arbeidet.

Keramikk har generelt lav tetthet og høy hardhet. Disse, og andre, egenskaper gjør materialet anvendbart for ballistisk beskyttelse. De vanligste keramikktypene som er benyttet i beskyttelsesløsninger er – i stigende rekkefølge med tanke på økt ytelse - aluminiumoksid, silisiumkarbid og borkarbid. Mekanismene som keramikk bryter sammen med ved høyhastighets anslag er relativt komplekse. De involverer feilmekanismer som for eksempel dannelse av radielle sprekker, dannelse av en kjegle gjennom keramikkplaten og fragmentdannelse som følge av mikrosprekker under anslagspunktet. Hvor mye hver enkelt mekanisme bidrar, og i hvilken rekkefølge de opptrer, avhenger av faktorer som anslagshastigheten, egenskapene til keramikken og prosjektilet, samt dimensjonene til keramikken og prosjektilet.

For å bedre ytelsen til et ballistisk beskyttelsessystem basert på keramikk, er det ønskelig å forsinke nedbrytningen av keramikken så lenge som mulig. Dette gir lenger tid til deformasjon og erosjon av prosjektilet. Det har blitt rapportert i litteraturen, og erfart gjennom arbeid utført ved FFI, at ulike metoder kan benyttes for å bedre den ballistiske ytelsen. Egenskapene ved ett eller flere anslag kan bedres ved å legge et annet materiale (for eksempel et fiberkompositt) rundt kanten av keramikken, ved å dekke keramikken med et lag av et annet materiale, og/eller ved å endre heften i grenseflaten mellom dette laget og keramikken.

Hovedmålet med denne rapporten er å gi en oversikt over mekanismene som er involvert i nedbrytning av keramikk, og beskyttelsesløsninger basert på keramikk, ved ballistiske anslag (det vil si ved dynamiske påvirkninger). Feilmekanismene, hvilke faktorer som kontrollerer feilmekanismene, og hva som kan gjøres for å forsinke nedbrytningen av keramikken, blir gjennomgått med grunnlag i utvalgt litteratur om disse temaene.

Contents

List of abbreviations

Al_2O_3 aluminium oxide.
AP armour piercing.

B_4C boron carbide.
BEV ballistic efficiency value.

DOP depth of penetration.

FEM finite element method.
FFI Forsvarets forskningsinstitutt.
FOI Totalförsvarets forskningsinstitut.

HP hot pressed.
HV Vickers hardness.

PC polycarbonate.
PU polyurethane.

RB reaction bonded.

SAPI small arms protective insert.
SiC silicon carbide.
SPS spark plasma sintering.

TNO the Netherlands Organisation for Applied Scientific Research.

UD uni-directional.
UHMWPE ultra-high molecular weight polyethylene.

WC tungsten carbide.

1 Introduction

Protection against high-velocity impact from objects such as projectiles is a major issue in many military and also civilian applications. In many cases, hybrid armour systems consisting of a *hard* ceramic strike face and a comparatively *soft* metal or composite backing are used for ballistic protection in both vehicles and body armour. The role of the ceramic is to erode and blunt the hard tip of the projectile, while the role of the backing material is to absorb the residual energy of the eroded projectile and the fragments of the fractured ceramic. One of the advantages of employing ceramics in hybrid armour, compared to materials such as steel and aluminium, is that more lightweight systems can be designed. The load on the vehicle or the soldier is reduced and the mobility is thereby improved.

Forsvarets forskningsinstitutt (FFI) has for many years been involved in the development of, and research on, lightweight body armour for ballistic protection of military personnel. In the period from 2004 to 2007, the technology for a SAPI plate was developed in a cooperation between FFI and industry. This technology is now used in armour systems that are employed by armed forces both nationally and internationally. For future developments of body armour, it is necessary to have knowledge about the mechanisms that are acting under ballistic impact of the armour. Knowledge about how the ceramics functions as stand-alone materials, and also how ceramic-based armour systems function, is important. Today, this topic is studied in several projects at FFI, and this report is written as a part of that work.

The main aim of this report is to give an overview of the mechanisms that are involved in ballistic (dynamic) failure of ceramics and ceramic-based hybrid armour. Hence, the report is not intended to give a complete overview of the literature in the field of ballistic failure of protection materials, but it discusses some important topics with respect to the dynamic behaviour of ceramic armour on the basis of the available literature.

Ballistic protection systems

Depending on scenario, the soldiers role and the mission, protection can be provided by several means among which a ballistic protection system can be a key part. Modern systems for ballistic protection of personnel is most often modular since different parts of the body need different levels of protection, and since not all missions require the same level of protection. For protection against fragments and projectiles, the main focus is on protecting the torso and the head, as an injury to these regions are generally more acute than injuries to other parts of the body. The protection against different types of threats that one might encounter is divided into protection levels in ballistic test standards. The protection level is essentially related to the ability to prevent a projectile from perforating the armour. In very general terms, a basic level of protection is a vest and a helmet that protects against fragments and most handgun projectiles. Both the vest and the helmet are usually made from sheets of ballistic fibres (polymers), such as aramid and ultra-high molecular weight polyethylene (UHMWPE). However, they are produced by different methods so that the helmet is stiff whereas the vest is relatively flexible. To increase the size of the protected area, protection to the crotch might be added (also made from ballistic fibres). Unfortunately, when the threats are projectiles from rifles, the ballistic fibres do not provide the necessary stopping power and other materials are needed.

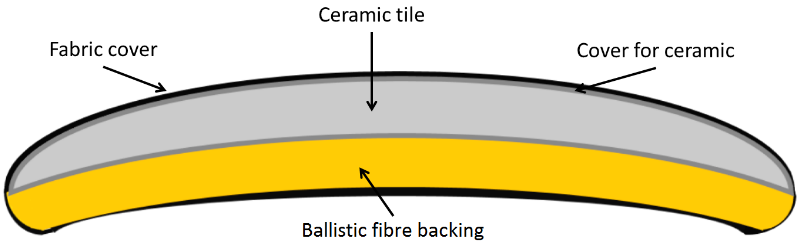

Figure 1.1 Schematic of the cross-section of a SAPI plate. A hard ceramic strike face is covered with a stiff composite material, often made from a glass fibre/epoxy fabric. The covered ceramic tile is backed by several layers of a ballistic fibre material, usually aramid or UHMWPE. Finally, the whole plate is covered in a tough fabric cloth to protect against UV-light and wear.

In order to stop armour piercing rifle rounds, a small arms protective insert (SAPI)-plate is often used in combination with the vest. Modern SAPI-plates are usually made from a combination of materials such as ceramics and ballistic fibres/composites. A typical layout of a SAPI plate is seen in Figure 1.1. The specific combination of materials, ceramic and fibres/composites, depends on the type of threats the plate has to be capable of stopping. The main component of the SAPI-plate is a thin (approximately 8 mm thick) tile made from a very hard ceramic. The ceramic blunts, erodes or fractures projectiles (even armour piercing) on impact. Unfortunately, ceramics are very brittle, thus the tile cracks and breaks into pieces on impact. To keep the ceramic from completely shattering, it is often covered in ballistic fibres or a composite material. Moreover, the ballistic fibres at the back absorb the majority of the kinetic energy and prevent the deformed projectile and the ceramic fragments from perforating the armour.

Outline of the report

The report is organized in sections. The sections cover topics such as a general description of armour ceramics, relevant test methods, failure mechanisms, and the effect of confinement, covering and adhesive bonding in ceramic armour. In the beginning of each section, a text box summarises the main findings of that particular section. Most of the literature that is discussed is on personal armour systems. However, the materials and the dynamic failure mechanisms are also relevant for other applications, such as vehicles and aircraft.

In the report, there is a focus on the literature dealing with ballistic characterisation, i.e. dynamic failure, of ceramic-based armour materials. Results from quasi-static characterization are covered only briefly. The reason for this is that it has proven very difficult to predict the ballistic behaviour of materials based on quasi-static material properties. Thus, results obtained from ballistic testing are much more relevant.

2 Armour ceramics

The low density and the high hardness of ceramics often make the use of them a better alternative in protection solutions than armour grade steel. Some of the important material parameters of armour ceramics are discussed in this section, together with an introduction to the three most used ceramics for armour purposes.

Main points on armour ceramics

- The most commonly used ceramics for armour purposes are aluminium oxide (Al_2O_3), silicon carbide (SiC) and boron carbide (B_4C).
- Al_2O_3 is usually the most economical alternative, but the final protection solutions with Al_2O_3 are heavier, since Al_2O_3 has the highest density and the lowest ballistic efficiency of the three ceramic types.
- B_4C is the hardest ceramic, but at high impact pressures an amorphization process weakens the ceramic. This is problematic when the threat is an armour piercing projectile at high velocity.
- SiC does not have the amorphization issue, but the density of SiC is higher than for B_4C.
- Low porosity in the ceramic generally results in better ballistic performance.
- Ceramics with small grain size usually performs better than ceramics with larger grain sizes.
- The production method influences the properties of the ceramic; hot-pressing often results in a harder ceramic optimal for single-hit, while reaction bonding often produce ceramics with better multi-hit performance.
- There is no clear correlation between the quasi-static mechanical properties and the ballistic behaviour of ceramics. However, some parameters such as the hardness, the fracture toughness and the elastic modulus are expected to have an influence.

2.1 Material parameters

One material parameter that is expected to have importance for the ballistic performance of the ceramic, is the *hardness*. The hardness is measured in an indentation test with a diamond indenter tip. There are two common shapes of the diamond indenter, a pyramid-shaped tip used in the *Vickers hardness (HV)* test and an elongated pyramid-shaped indenter with a length-to-width ratio of 7 to 1 in the Knoop hardness test. The results for the two hardness tests cannot be directly compared. A high hardness of the ceramic is desirable, since a material with a sufficiently high hardness will deform or fragment a projectile upon impact [1]. Moreover, if the ceramic tile is fragmented by the projectile, a high hardness of the ceramic fragments will result in more abrasion of the projectile during the rest of the penetration process [2, 3]. It is, however, not clear if harder is always better, since one of the main failure modes of the thin ceramic tiles in armour solutions is due to fracture from tensile stresses, which is something a higher hardness does not improve.

Avoiding or postponing the failure of the ceramic is crucial for the protection capability. To achieve this, the ceramic has to be able to withstand the tensile stresses that occur upon impact, e.g. the bending stresses on the back side of the ceramic tile. The material parameter *fracture toughness*, K_{IC}, can give an indication of the performance of the ceramic; the higher the value - the better performance [1]. The fracture toughness can be found from the size of cracks initiated in the corners of the indentation from a Vickers hardness test.

Krell and Strassburger [3] mention the correlation between the *elastic modulus*, E (also called Young's modulus), and the ballistic performance of ceramics. A ceramic with a high elastic modulus will have a smaller strain for a given stress (than a ceramic with a lower value of E), thus resulting in a faster increase in stresses in both the projectile and the ceramic. This might result in more shattering of a hard and brittle projectile core. Moreover, a high value of the elastic modulus also results in a high speed of sound in the ceramic, since $c \propto \sqrt{E}$, where c is the speed of sound. A higher speed of sound allows for a faster spreading of the load, thus activating a larger region of the ceramic tile.

There are other material parameters, that may have an influence on the ballistic performance of a ceramic, such as a high *tensile strength*, as well as a low *porosity*. Holland and McMeeking [4] mention a positive correlation between the fracture strength (and thus also the ballistic performance) and an increasing *Poison's ratio*, ν, and similarly for an increase in the *density*, ρ. Regarding the density, it should be kept in mind that although a higher density often results in better ballistic performance, this may not be true when the ballistic performance is compared on the basis of areal density.

Some of the above-mentioned material properties can be combined in the D-criterion [5, 6]

$$D = \frac{0.36\,(HV \cdot E \cdot c)}{K_{\mathrm{IC}}^2},$$

where c is the speed of sound in the ceramic. The D-value is a measure of the ability of the ceramic to absorb energy upon impact. It matches the discussion above, since both an increase in hardness and elastic modulus result in a higher value of D. However, the dependence of the fracture toughness, K_{IC}, is the opposite of what might be common belief. This is due to the fact that the D-value is for one-hit performance, where apparently a lower value of K_{IC} is desirable, whereas for multi-hit a high fracture toughness is needed [6].

2.2 Ceramic microstructure

The somewhat divergent effects of the fracture toughness on ballistic performance of ceramics, is an example of the difficulty of directly correlating a specific material parameter with the ballistic performance. This is not only true for the fracture toughness but also for other parameters, such as the hardness and the elastic modulus. There are several examples of ceramics with high hardness that perform worse than less hard materials, and the same is true for elastic modulus. The question is then; why is it so?

Krell and Strassburger [3] discuss the correlation between a set of material parameters and the ballistic performance, and give some of the answers to this question. They studied the influence of the microstucture of the ceramic on both ballistic performance and also on material properties. What they found was, somehow not surprisingly, that the microstructure of the ceramic has a large influence on the material properties of the ceramic. Generally, for a ceramic, a smaller grain size results in higher hardness. This means that in experiments where the ballistic performance is improved with increasing ceramic hardness, the ballistic performance may actually be an effect of changes in the microstructure of the ceramic. Thus, establishing a direct correlation between one material parameter and the ballistic performance may be a challenge when the microstructure is different, and care should be taken when analysing results where mechanical properties are affected by the microstructure. This does not mean that a high hardness or elastic modulus is not generally good for ballistic performance, since Krell and Strassburger also found positive correlations for these parameters.

One of the interesting results in the study by Krell and Strassburger [3], is on the ballistic performance of a high quality (small grain size) Al_2O_3 powder subjected to poor processing, compared to a low quality (large grain size) Al_2O_3 powder that was properly processed. The result was that the high quality, but poorly processed, Al_2O_3 powder outperformed the well-processed large grain sized Al_2O_3 powder. This result highlights the importance of the quality of the initial powder used for ceramic production. Moreover, it exemplifies the importance of having small grain size.

However, a high quality material may not in itself give good penetration resistance. A comparison of Al_2O_3 ceramic vs. sapphire (which is single-crystalline Al_2O_3) showed that a low quality Al_2O_3 ceramic performs better than sapphire, despite the better material quality and higher hardness of sapphire [3]. One reason for this difference is the mechanisms for fragmentation. The sapphire fractured into small, fine fragments when impacted, whereas the Al_2O_3 ceramic fractured into larger fragments. Fragmentation into larger fragments is desirable since larger fragments are harder to move out of the way for the penetrator, and thus results in a higher penetration resistance and more abrasion of the penetrator. Another reason for the lower performance of a single crystal sapphire is its lower fracture toughness.

2.3 Commonly used armour ceramics

The ceramic tile in a SAPI-plate is usually made from either Al_2O_3, SiC or B_4C. There are other ceramics that can be used for body armour purposes, but the three mentioned types are by far the most common. The choice between these types of ceramic materials depends on several parameters/requirements, amongst which threat level, weight restrictions and price are dominating. Unfortunately, a comparison of the performance of these three types of ceramics is not as straightforward as one might desire. As discussed above, Al_2O_3 is not just Al_2O_3 - the quality and purity of the raw materials and the processing methods have a large influence on the performance of the final product.

Aluminium oxide

The most economic type of armour ceramic is aluminium oxide (Al_2O_3), also called alumina. It has, however, also the highest density of the three mentioned types of ceramics. The density of Al_2O_3 for armour purposes is in the range of $3.6\,g\,cm^{-3}$ to $4.0\,g\,cm^{-3}$ [7, 8], depending on the purity (90 % to 99.95 %) and the final porosity of the product (<2 %). One might think that the lowest density is preferred since this would be expected to give a lower mass of the SAPI-plate. It is, however, generally the opposite way around. A higher purity and lower porosity does give a higher density, but a more pure and less porous Al_2O_3 performs better in ballistic testing. Thus, a thinner ceramic tile is needed in the SAPI-plate for the same (or better) ballistic performance.

Boron carbide

A low porosity is also desired for the two carbides, SiC and boron carbide (B_4C). However, when it comes to the purity, the effect is less clear for these ceramics. A high purity in the raw material is desireable for both SiC and B_4C, but since these two materials are often used together, a ceramic tile with 80 % B_4C is not necessarily of poor quality. Of the two carbides, B_4C has the lowest density, theoretically $2.52\,g\,cm^{-3}$ [9], but it is also generally the most expensive. B_4C is roughly twice as hard as Al_2O_3, depending somewhat on the production method, and is among the hardest known materials. The high hardness combined with the low density suggest that B_4C would be the top candidate for ballistic protection, and in many cases it is. However, when it comes to stopping an armour piercing projectile at around muzzle velocities, B_4C does not perform as good as tests at lower velocities suggest. This is thought to be due to an amorphization process that occurs in the B_4C material when the pressure reaches $\sim$20 GPa, which is roughly the pressure reached during impact at muzzle velocities of armour piercing projectiles [10]. At this pressure, the shear strength of the B_4C ceramic drops dramatically, and the ballistic performance is reduced. This is obviously a problem, but it does not mean that B_4C is not a good option. Another problem with B_4C is that it is very brittle, especially hot pressed (HP) B_4C. HP B_4C is a good option for one-hit protection, However, when multi-hit performance is needed, reaction bonded (RB) B_4C is often used. RB B_4C often contains some SiC to adjust the performance.

Silicon carbide

As mentioned, silicon carbide (SiC) is often mixed with B_4C, but armour ceramics from primarily SiC are also common. The theoretical density of pure SiC is $3.21\,g\,cm^{-3}$ [11], thus in-between that of B_4C and Al_2O_3. However, addition of other materials in order to improve performance often result in a final density that is lower than the *theoretical* value for pure SiC. SiC has a hardness that is very close to that of B_4C. Thus, when protection against threats that can produce impact pressures above $\sim$20 GPa (7.62 mm or larger armour piercing threats, or impact at higher velocities), SiC is often a better choice than B_4C, in spite of its higher density. Just as in the case with B_4C, the production method has a large effect on the properties of the ceramic.

Production methods

As discussed above, carbide ceramics can be produced by different methods, and each method produces ceramics with slightly different properties. RB ceramics are usually better for multi-hit performance, but the single-hit performance is usually not as good as for ceramics produced by HP. The brittle ceramics produced by HP are, however, not that good for multi-hit. A promising new production technique, spark plasma sintering (SPS) is very energy intensive, but the final products are of superior quality. The technique is getting close to a maturity level where realistic sized ceramic tiles can be produced at reasonable costs.

For a more thorough discussion on the above mentioned ceramic materials and the production methods, reference [12] is recommended for further reading.

3 Methods for ballistic testing

Ballistic testing of body armour materials can generally be divided into two groups: (1) Testing of complete armour systems, such as for example a SAPI-plate used in combination with a flexible vest, and (2) testing of components that are used to build armour systems, such as for example ceramics or ceramics that are confined or covered by another material. Test methods for both groups are briefly described in this section. The review article by Normandia and Gooch [13] provide a good starting point for the various methods that are available for testing of ceramic armour.

Main points on ballistic testing methods

- Several standards exist for evaluating protecting systems including the commonly used NIJ 0101.06 and STANAG 2920 standards.
- When evaluating complete protection systems, the backface signature and the ballistic limit are commonly used as measures of performance.
- For evaluation of the components used in a complete armour system, they are often tested individually and not as part of a system.
- The DOP test and the V_{50} test are among the most used methods for ranking and studying the performance of ceramics.
- The newer energy-method may allow for more information to be collected from fewer tests.
- The ballistic performance of a ceramic tile is affected by the lateral dimensions of the tile. If the tile is too small, stress wave reflections from the edges reaches the interaction region too rapidly, which results in a lower ballistic performance.
- At hypervelocity, the edge effects become negligible as the time for the edge-reflection of the stress wave to reach the impact position is less affected by the impact velocity.

3.1 Complete armour systems

Several test standards exist for evaluating protection systems, amongst which NIJ 0101.06 and STANAG 2920 are perhaps the two most frequently used or referred to [14, 15]. In these standards, the armour panel to be tested is strapped to a backing material made of modeling clay. Typically, two parameters are tested in evaluation and certification of armour; (1) perforation and backface signature (P-BFS) and (2) ballistic limit.

In perforation and backface signature (P-BFS) testing, the backface signature (BFS), or the trauma, is the defined as '*the greatest extent of indentation in the backing material caused by a non-perforating impact on the armour*' [14]. The indentation in the clay is measured after each shot, and a typical requirement is that the depth should be no more than 44 mm. Typically, 24 fair hits are required, whereas a complete perforation of the armour constitutes a failure.

The ballistic limit is defined as '*the velocity at which the bullet is expected to perforate the armour 50 % of the time*' [14]. The ballistic limit is typically denoted as the V_{50} value. The V_{50} velocity is calculated as the arithmetic mean of an even number of shots, where one half of the shots gave no or only partial perforation, and the other half of the shots gave full penetration. Depending on the protection level of the armour, 12 or 24 shots are typically required in order to obtain reliable results. In a similar manner, it is also possible to test for the highest velocity where no penetration occurs, V_0, or the lowest velocity that always results in penetration, V_{100}, although these tests are not described in the cited standards.

Anyway, when taking into account P-BFS and ballistic limit testing, it is obvious that a high number of tests is required to obtain reliable results for armour. Furthermore, in certification of body armour, it is also a requirement that the armour is conditioned prior to testing, which increases the number even further.

3.2 Armour components

Most lightweight systems for ballistic protection are combinations of different material components. The main aim of both armour systems producers, armour materials producers, and for researchers working in the field, is to develop the best possible armour systems. The armour systems can be characterized by the methods described in the previous section. However, the armour components are not easily characterized by these methods. Instead, several other methods are used to characterize the components of an armour system individually, such as for example the ceramic tiles. It should be kept in mind, however, that the specific performance of e.g. a bare ceramic not necessarily gives information about how the ceramic performs as a component in a complete armour system, and how it performs against another type of threat than it was tested for, although it will give an indication of the performance. Nevertheless, it is important to evaluate the ballistic performance of the components, and also to evaluate the failure mechanisms and the effect of process parameters. This is easier to achieve on a component level, since the complete armour systems are more complex, which makes it more difficult to identify the origin of different test results.

Depth of penetration

One of the most used test methods for ranking and comparing ceramics is the depth of penetration (DOP) test. In this test, the ceramic tiles are glued to thick (75 mm to 120 mm) backing blocks and then shot with the projectile that one want to compare the performance against [16–18]. The projectile first penetrates the ceramic and then penetrates further into the backing block. Depending on the ability of the ceramic to erode and slow down the projectile, the penetration into the backing block can be either long (low performing ceramic) or short (good ceramic performance). A simple sketch of the test setup is shown in Figure 3.1.

The backing block is often made from an aluminium alloy [16], since aluminium has a high enough elastic modulus to support the ceramic, without being too hard or tough to penetrate into for the partly shattered and slowed down projectile. The downside of using aluminium is that in order to find the penetration distance, the aluminium block has to be cut or X-rayed. To avoid this, a block of polycarbonate (PC) can be used instead of aluminium [17]. The PC material is transparent, and the

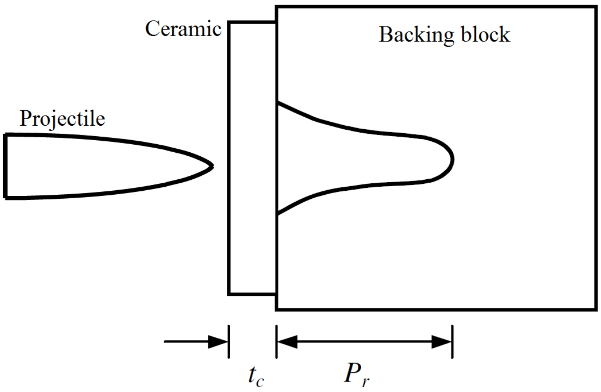

Figure 3.1 The DOP test setup. t_c *is the ceramic tile thickness and* P_r *is the penetration distance into the backing block. Reprinted with permission from Hazell et al. [17].*

penetration distance into the block can be found without any cutting or X-raying.

The DOP-test is a feasible method for comparing the performance of different types or varying thickness of ceramic. The shortcoming of the test method is that a relatively large number of tests are required, since the repeatability of the method is not optimal with sometimes large variations in the results [19]. Moreover, in the DOP-test the ceramic performance is evaluated with a thick backing, which is comparable to how the ceramic is used in real armour solutions for personal protection. The test is, however, a tool in combination with other test methods that do not require a thick backing material.

V_{50}

As described above, the ballistic limit test, or V_{50} test, is employed for armour systems. The V_{50} test is also a common test method for evaluation of bare ceramics and of more complex components. The disadvantage of using this test on ceramic-based targets is the number of tests that have to be performed, since one shot can typically only be used for each target. (For armour systems, it is common to fire several shots at each target). It is, however, a useful test since it gives quantitative values of the ballistic performance, and since no other materials (such as a witness plate or ballistic clay) are used in the tests. This also makes the test applicable for comparison with simulations. Examples of use of the V_{50} test can be found in [20, 21].

Energy method

A test that has many similarities with the V_{50} test, is a test where the residual velocity of the penetrator is used as a measure of ballistic performance. In such tests, the initial, V_{init}, and the residual velocity, V_{res}, of the penetrator are compared among several test samples. However, the ballistic performance is often evaluated by comparison of the initial kinetic energy, E_{init}, and the residual kinetic energy, E_{res}. The kinetic energy is found by $E = {}^{1}/_{2}mV^2$. This is a more precise measure of ballistic performance, since it takes into account the residual mass of the penetrator. However, this also means that the penetrator has to be collected after perforation of the target in order for the energy to be calculated. The advantages of this method are, similar to the V_{50} test, that a measure of the (important) capability of the armour system to erode the penetrator can be found from the residual mass of the penetrator, and also that a comparison with numerical simulations is possible. A clear disadvantage of the test is, that it only compares armour systems that have failed since a prerequisite for comparison is perforation of the targets. Sarva et al. [22] used this method to study the effect of covering of ceramic tiles.

The Netherlands Organisation for Applied Scientific Research (TNO) has implemented the above-mentioned comparison of energies (E_{res} and E_{init}) in a ballistic test method denoted the '*energy-method*'. In the experimental setup, shown in Figure 3.2, the initial velocity is measured by a set of laser screens, while the residual velocity of the penetrator can be estimated from high speed filming of the cloud of ceramic debris that is observed behind the target. The penetrator itself is obscured by the ceramic debris, but it is assumed that the residual velocity of the penetrator and the velocity of the ceramic cloud are the same. The fragment catcher at TNO is a water tank, although any type of soft catch method can be used. From the calculated energies, a measure of the *ballistic efficiency value (BEV)* can be found by

$$BEV = \frac{E_{\text{init}} - E_{\text{res}}}{AD},$$

where AD is the areal density (mass per unit area). A higher value of *BEV* indicates a higher ballistic performance. Besides getting an estimate of the ballistic performance in terms of energy loss of the projectile, the energy-method can also be used to estimate the dwell time of the penetrator. The concept of *dwell-time* is explained in Section 5.2. The dwell time can be found by converting the residual projectile mass into a residual length after impact. The difference in penetrator length before and after impact, ΔL, is then used together with the impact velocity, V_{init}, to find the dwell time by

$$t_{\text{dwell}} = \frac{\Delta L}{V_{\text{init}}}.$$

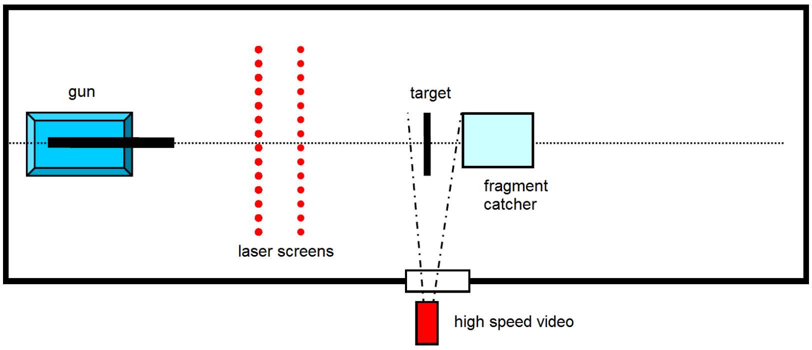

Figure 3.2 The experimental setup in the energy-method used at TNO. Reprinted with permission from Carton and Roebroeks [23].

Tile size effects

In a study by Hazell et al. [17], it was shown that the performance of individual ceramic tiles increased with tile size in a DOP test. They concluded that for impact of an 7.62 mm armour piercing (AP) projectile on a 7.5 mm thick liquid phase sintered SiC tile, the size has to be at least 70 mm × 70 mm. If the tile size is smaller than this, the performance drops due to edge effects. In the same study, it was also shown that the position of impact on the tile is important. When the impact zone is closer to the edge, the ceramic performance drops due to edge effects. This finding on the importance of the lateral dimensions of the ceramic tiles is supported by results from TNO. Carton and Roebroeks [23] found that the energy loss of a 7.62 mm AP projectile on a 8 mm thick Al_2O_3 tile dropped steeply for tiles sizes smaller than 60 mm × 60 mm. For larger tiles, the size effect was less significant.

The edge effects and thus tile size effects have been found to be less significant when the impact velocity is much higher than the typical velocities of bullets fired from rifles. Chocron et al. [24] found that the influence of the impact position and the edge distance became lower when the impact velocity increased. At $3.5\,\mathrm{km\,s^{-1}}$, no difference in penetration was observed. This behaviour was explained by the authors to be related to a change in the penetration mechanics at the high velocities. At lower velocities (rifle muzzle velocities), the strength and the lateral confinement have a large effect on the penetration process, whereas at increased velocities, the density of the material is the controlling parameter.

4 Failure mechanisms of ceramics

Ceramic materials can fracture in a number of different ways when impacted by a hard projectile at high velocities. The failure mechanisms, and the factors that govern the onset of these mechanisms, are discussed in this section.

Main points on failure mechanisms in ceramics

- The chronological order of the damage mechanisms observed in ceramics upon impact vary with tile/penetrator dimensions and material properties.
- Comminution (crushing) in the region beneath the penetrator is the result of micro-cracking and plasticity in the individual crystal lattices. High tensile and shear stresses result in cracking, followed by crushing by the high compressive stresses.
- Ceramic materials are stronger in compression. The stress state directly beneath the penetrator is compressive, and this region is often less damaged compared to regions deeper into the ceramic, which are subjected to more tensile stresses.
- Formation of a surface ring crack can occur just outside the contact region between the penetrator and ceramic. Large tensile stresses propagate further into the ceramic at an angle to the surface, yielding a cone shaped crack - thereby the name cone crack.
- Pressure waves that are reflected on the backside of the ceramic give rise to large tensile stresses that result in cracks moving radially outwards on the backside of the ceramic tile.
- Radial cracks and cone cracks are the dominant failure modes at moderate velocities (below $\sim 400\,\mathrm{m\,s^{-1}}$). Radial cracks are most prominent for thin plates, but often depressed in thicker plates.
- Lattice plasticity and micro-cracking are also prominent failure mechanisms at higher impact velocities.

4.1 Dynamic failure

The strain rates obtained during dynamic impact are very high and the mechanisms that govern the damage evolution are more complex than what is observed at quasi-static strain rates. Compton et al. [25] describe four common failure modes observed in ceramics upon impact; lattice plasticity, micro-cracking, radial cracks, and cone cracks. These failure modes are shown in Figure 4.1. The cone and radial cracks are observed on the larger scale, whereas the micro-cracking and the lattice plasticity occur in the region just below the impactor.

Lattice plasticity is related to failure of the crystal structure in the ceramic grains. One failure mode is dislocation glide/creep, where a dislocation moves in the lattice due to the applied stresses. In such a dislocation glide, the atoms can move a number of lattice spacings until they reach the grain boundary, or for instance a point defect. In the process called twinning, on the other hand, a shear force produces atomic displacements resulting in a homogenous deformation. The lattice structure is then rearranged.

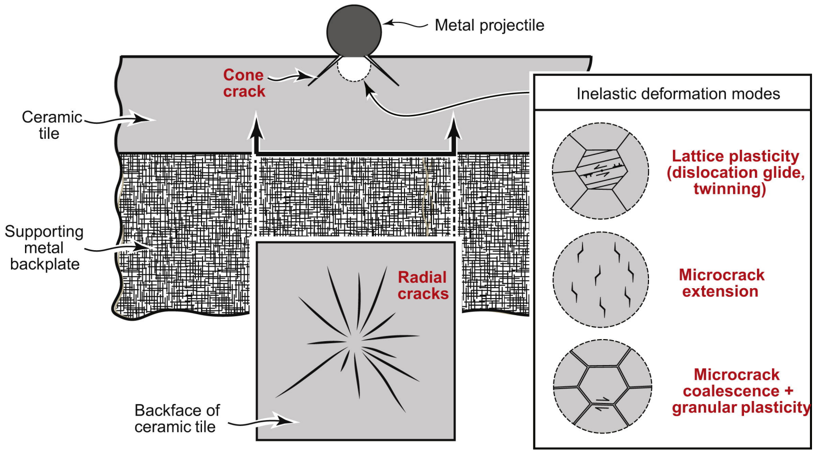

Figure 4.1 Different damage modes in a ceramic tile. On the front of the ceramic, cone cracks are often formed upon impact, while radial cracks are initiated on the backside of the ceramic tile. Reprinted with permission from Compton et al. [25].

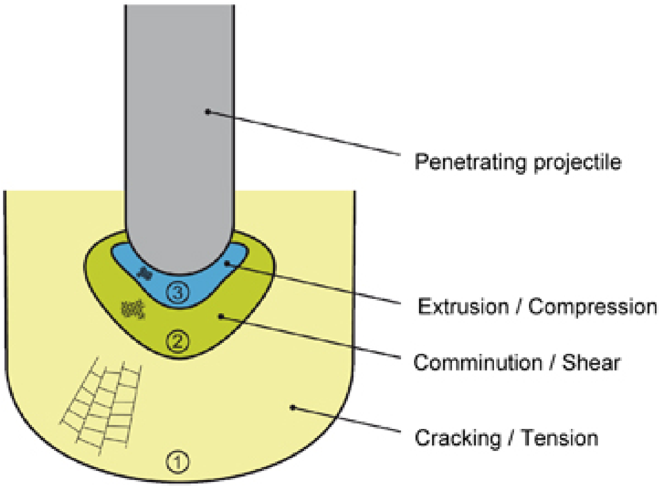

Figure 4.2 Process zones and stress states. Reprinted with permission from Shockey et al. [26].

In micro-cracking, the cracks can be both inter-granular and trans-granular. A trans-granular crack extends across one ceramic grain, while an inter-granular crack follows the grain boundaries. Since they follow the grain boundaries, inter-granular cracks are not as straight (more jagged) than trans-granular cracks. Shockey et al. [26] explain the formation of these micro-cracks underneath the penetrator as occurring '*in three successive steps under consecutive tensile, shear and compressive states*' as shown in Figure 4.2. The material in front of the penetrator is becoming heavily cracked by the tension and shear stresses, and next the compressive stresses crush (comminute) the ceramic into fine fragments. If the penetration continues, these small fragments are pushed outwards and forced to move against the penetrator, resulting in further erosion of the penetrator. Lankford [27] explains that the movement of the comminuted ceramic in the lateral direction underneath the penetrator is a result of inadequate confinement around this region. Around the edge of the penetrator, the comminuted ceramic pieces can move due to the lack of confining material, and the state of the ceramic is changed from being comminuted to being a powder. The difference between the two states is that the comminuted ceramic pieces are interlocked and prevented from moving due to the surrounding material, while the powder state has lost this interlocking, as illustrated in Figure 4.3. The stress-strain response curve for comminuted ceramic is three to four times steeper than for powder ceramic under dynamic loading, which means that the comminuted material is significantly stronger than powder. This suggests that, in order to increase the performance, it is important to prevent the ceramic fragments from moving outwards (or away from the interaction region) during impact.

The difference in ballistic performance between comminuted ceramic and ceramic powder has been investigated for Al_2O_3 by Horsfall et al. [28]. They compared the performance of ceramic powder, a ceramic tile that was shattered/comminuted by the shock wave from an explosive loading, and an intact ceramic tile. All three samples were under compression during testing. The results showed that the ballistic performance measured in a DOP-test was reduced by 30 % for the comminuted ceramic, while the ceramic powder had a 40 % lower performance compared to the intact tile. This shows that a damaged (in this case comminuted and powder state) ceramic, maintains some ballistic performance, and that a comminuted material performs better than the more free-flowing powder. This conclusion is in line with the suggestions by Lankford [27].

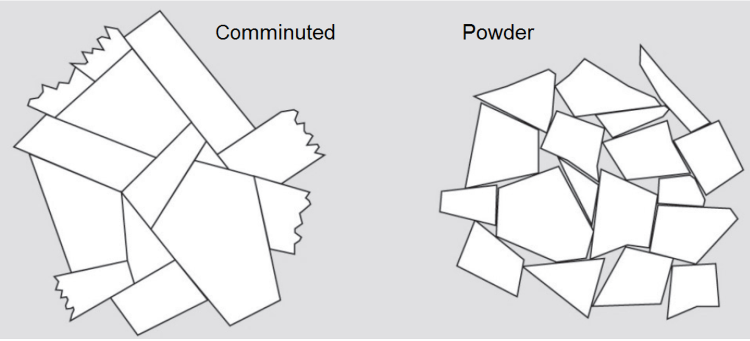

Figure 4.3 Depiction of the difference between comminuted ceramic and ceramic powder. Reprinted with permission from Lankford [27].

In Figure 4.1, the radial cracks are shown on the backside of the brittle ceramic. However, there is also a possibility of having radial cracks directly underneath the impacting projectile. These median-radial cracks are often observed in quasi-static indentation tests with sharp indenters (Knoop and Vickers). The median cracks initiate due to tensile stresses underneath the indenter/impactor and grows from the top of the specimen towards the backside, but do not necessarily reach the back. The other type of radial cracks initiate on the backside of the brittle specimen, directly beneath the impactor, due to bending stresses (tensile stresses) created by the impacting projectile on the front-side [29]. These cracks move outwards from the centre and are arrested at the edges of the specimen, or sooner if the stresses are relieved. Besides moving outwards, these radial cracks also move towards the front of the specimen as the tile is being bent. The number of radial cracks on the backside have been shown to increase with increasing impact velocity for both ceramics, glass and a brittle plastic [29, 30]. It has also been shown that pressure required to initiate the radial cracks depend on the backing material. This will be discussed further in Section 5.

4.2 Quasi-static failure

As mentioned in Section 2, the strain rates that are reached during projectile impact on ceramics are very hard to replicate in a controlled experiment. Fortunately, many of the features and mechanisms that are observed in the more easily controlled quasi-static experiments can also be seen in dynamic impacts. One of these is the creation of so-called Hertzian cone-cracks. Usually, the cone cracks are observed in experiments were a sphere, often made from hard steel or tungsten carbide (WC), is pressed into a thin glass or ceramic tile [31]. In the first part of this indentation process, the sphere is slightly deformed but, when the stress field in the ceramic reaches a critical value, a surface ring crack is formed in the thin glass/ceramic tile just in the vicinity of the edge of the contact region. Next, the ring crack continues as a cone crack further into the thin specimen, where it follows the path of the greatest tensile stress [32]. An image showing both the surface ring crack and the cone crack is shown in Figure 4.4. These conical cracks are very often observed in impact tests on ceramic tiles and are very important for distributing the impulse from the impact onto a larger area on the backside of the ceramic tile.

4.3 Damage evolution

The failure mechanisms discussed above show that the main reason for the cracks to initiate in ceramics is tensile stresses. The ceramics are weakest in tension and strongest in compression. Directly underneath the projectile, the compressive stresses can become large enough to damage the ceramic. However, at this point, the stresses in the projectile are also high enough to heavily damage the projectile. The above-mentioned failure mechanisms can occur at the same time or subsequently, depending on the ceramic and projectile material, the relative dimensions and shapes of these, and on the impact velocity. Furthermore, the relative timing of the failure mechanisms is affected if the ceramic is covered or confined by other materials. For instance, Compton et al. [25] found that varying the impact velocity ($0.5\,\mathrm{m\,s^{-1}}$ to $850\,\mathrm{m\,s^{-1}}$) of a metal sphere onto Al_2O_3 resulted in differences in the relative timing of the crack initiation.

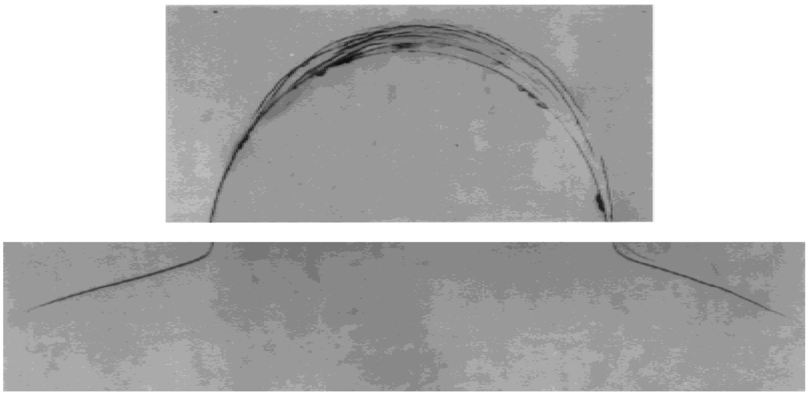

Figure 4.4 Photographs showing a Hertzian cone-crack in silicon nitride in both front- and inside-view. The initial ring crack and the subsequent cone crack are observed in the inside view. Reprinted with permission from Lawn [31].

Compton et al. [25] also summarised the results from a numerical and analytically study of a steel sphere impacting on Al_2O_3, as shown in Figure 4.5. The figure shows the dominant failure modes as a function of impact velocity and the ratio between tile thickness, h, and projectile (sphere) radius, R. The first conclusion from the graph is that the occurrence of radial cracks depends on the normalised tile thickness, h/R, i.e. higher normalised tile thickness requires higher impact velocity to initiate radial cracks on the backside of the ceramic. The other modes (cone cracks, lattice plasticity, and micro-cracking) do not show the same dependence on normalised tile thickness, but depend primarily on the impact velocity. This is because these failure modes are initiated on the front of the tile or directly underneath the projectile. Moreover, the graph shows that while the radial cracks are dominant for thin tiles, they become less dominant as the normalised tile thickness increases.

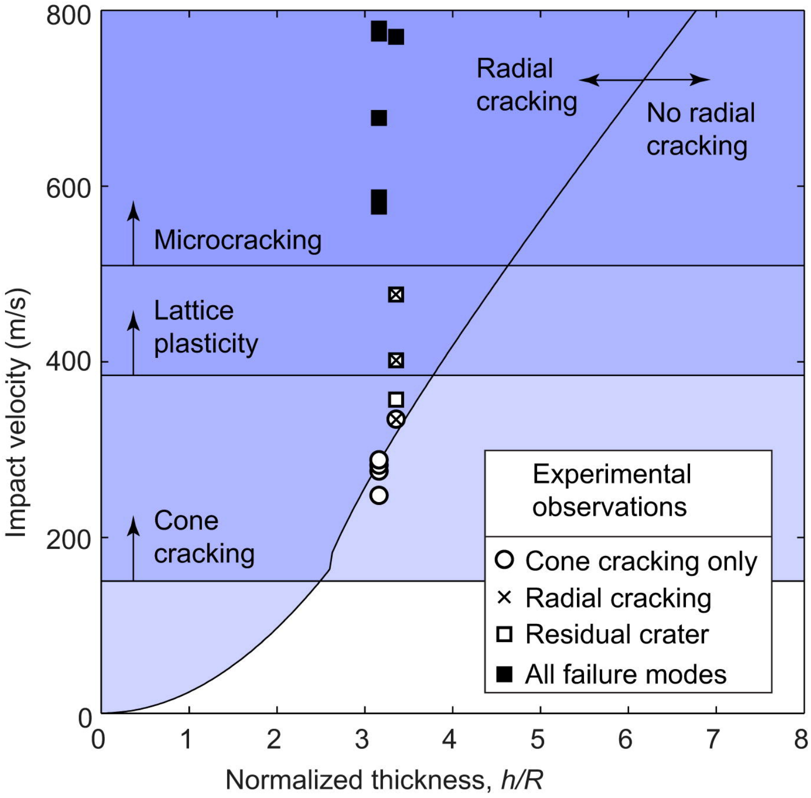

Figure 4.5 The dominant failure modes for a steel sphere impacting an Al_2O_3 *tile. The normalised thickness is the ratio between tile thickness, h, and sphere radius, R. Reprinted with permission from Compton et al. [25].*

5 Confinement and covering of ceramics

As discussed in Section 4, ceramics fracture in a brittle manner when subjected to high tensile stresses, thus creating fragments of varying size. Covering the ceramic with a sheet material is a common method of holding the fragments together. Thus, the integrity of the ceramic is partly maintained during and after impact. Moreover, applying confining pressures on the ceramic can alter the failure mechanisms and improve the performance of the ceramic. The effects of adding a cover and/or a confining pressure to ceramics are discussed in detail in this section.

Main points on confinement and covering

- A cover or backing layer on the backside of the ceramic can also improve the performance. Hard and stiff materials give higher improvements compared to softer materials. Less reflection of the pressure wave on the backside of the ceramic is causing the increased performance.
- A front cover on the ceramic usually improves the single-hit performance. The ceramic fragments underneath the penetrator cannot move out of the way of the penetrator, thus increasing the load on the penetrator.
- Covering the ceramic with a composite material can improve the multi-hit performance. The integrity of the ceramic tile is not lost after the first impact.
- Adding a cover to the ceramic changes the fragmentation of the ceramic. A covered ceramic is more highly fractured.
- There is likely an optimal thickness of the cover layers in terms of ballistic performance versus total weight. The cover thickness is often less than 1 mm.
- A damaged ceramic tile may give only minor performance reductions if covered by a composite material (∼7 % in one study, ∼3 % in another).
- Pre-stressing the ceramic by lateral confinement results in increased ballistic performance of the ceramic. Ceramics are pressure hardening materials, and their strength under compression increases.
- The dwell-time is the time period from projectile impact to the projectile actually starts penetrating the target. The projectile is eroded and the ceramic is kept intact. A key to improve armour performance is to increase the dwell-time.

5.1 Covering of the ceramic

In a paper from 1990 by Shockey et al. [33], the failure mechanisms of thick (25 mm) ceramic blocks during impact of a steel sphere at moderate impact velocities, or a long rod at high velocities, were described. Their findings were similar to the works presented in Section 4 (which are all of a more recent date). At lower velocities, the first failure mode that occured was ring crack formation on the ceramic surface, then as the velocity increased, formation of cone cracks followed. Next, an inelastic deformation underneath the impact zone was observed together with radial cracks. With increasing velocity, formation of lateral cracks and median cracks were found[1]. It is important to note here that the above failure modes all occurred without any penetration into the ceramic. The cracks explained above do not give the penetrator a path through the ceramic if the ceramic fragments are not pushed out of the zone ahead of the projectile. Thus, these larger fragments have to be moved out of the path or even smaller fragments have to be produced in the path. Moving the larger fragments may be possible for very thin ceramic tiles that are not properly backed. However, in the words of Shockey et al. [33], '*the development of a densely microcracked zone in a ceramic directly ahead of the impactor is a prerequisite of penetration*'. So, preventing penetration is a matter of making the formation of this microcracked/comminuted region as difficult as possible. When fragments or particles are formed, they should 'disturb' the penetrator as much as possible by staying in the path of the penetrator for as long as possible.

The importance of holding the larger ceramic fragments in place in the path of the penetrator, is one of the reasons why ceramic tiles in SAPI-plates are often covered in a ballistic polymer or a composite material. This prevents the fragments produced during impact from moving and is thus expected to improve the performance of the ceramic. Several studies have been performed on the effect of penetration resistance of covered ceramics. However, before discussing these studies, it is appropriate to first discuss what can be done to avoid or postpone penetration in the first place.

5.2 Long rod penetration in thick ceramic discs

Radial confinement

Lundberg and coworkers at Totalförsvarets forskningsinstitut (FOI) have thoroughly studied the penetration of long rods into ceramic targets [34–37]. A main focus point of the work was to study what happens when the projectile is inhibited from penetrating the ceramic, and then what happens when the projectile starts penetrating the ceramic. In impact situations where the long rod does not have high enough velocity to penetrate the ceramics, the material in the front of the rod is forced to flow outwards, since the rear part of the rod continues to move towards the impact zone. This situation is called interface defeat of the penetrator, since it is defeated in the interface between the penetrator and the ceramic. The time period of the interface defeat lasts from the first impact until penetration of the ceramic occurs. This time period is also called the *dwell time*. Increasing the dwell time is favourably, since the penetrator/projectile is being eroded during this period. The penetration into the ceramic starts when the comminuted region, which is initiated at the depth in the ceramic with the highest elastic shear stresses, has expanded and reached the surface [34].

In the experiments, Lundberg *et al.* studied the impact between the long rods and a ceramic disc confined in a metal cylinder, which prevents the ceramic from expanding/flowing outwards radially. In one of the studies [34], the transition velocity (the velocity above which the penetration occurs) was found for different materials upon impact with a tungsten rod; TiB_2, two types of SiC, B_4C, and a diamond composite. From the yield strength of the materials (based on Vickers hardness

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[1] With the results of Compton et al. [25] in mind, see Section 4, the relative order of the failure modes described by Shockey *et al.* could have been somewhat different if the ceramic tile thickness and projectile radius had been different.

indentation tests), lower and upper bounds of the transition velocity could be estimated theoretically. Interestingly, the experiments showed that for the two types of SiC and the TiB_2, the transition velocity was close to the upper bound, while for the two hardest materials, B_4C and the diamond composite, the transition velocity was closer to the lower bound. Moreover, the transition velocity was lowest for the B_4C, although its yield strength was higher than both SiC and TiB_2. This suggests that the hardness and yield strength are not necessarily direct indicators of performance. In another study, a small positive effect was found when increasing the thickness of the steel confining tube [35]. This increase in performance was suggested to be due to the ceramic being capable of retaining resistance to penetration somewhat longer with the thicker support on the edges.

In an attempt to study the correlation between the measurable mechanical properties of ceramics with penetration resistance, four different SiC materials were tested by Lundberg and Lundberg [36]. The four SiC ceramics had different Vickers hardness values and different values for fracture toughness. The experimental study did not show any clear correlation between the hardness value and the transition velocity of the ceramic. However, the transition velocity was found to increase with higher fracture toughness. This suggests that fracture of the ceramic has higher influence on the interface defeat than plastic flow. Thus, suppressing crack initiation and propagation in the ceramic might further increase the transition velocity.

The shape of the tip of the penetrator was found to have a large influence on the transition velocity in the long rod experiments [37]. When changing the usual flat cylinder penetrators to penetrators with a conical tip, the transition velocity (from interface defeat to penetration) was found to drop. This can partly be explained by the increase in surface pressure beneath a conical tip, and X-ray images of the penetration process showed that the flow of penetrator material into conical cracks in the ceramic was more pronounced for conical tip penetrators. This was suggested to be due to a larger radial growth of surface load for conical tip penetrators.

Radial confinement and front covering

In the studies by Lundberg and co-workers discussed above, the ceramic was radially confined by a steel cylinder. This radial confinement is effective in preventing the ceramic fragments from flowing outwards, and also in preventing the ceramic from moving in the direction of the projectile (by adding a backing material). The importance of having a front cover on the ceramic may not be obvious, but it is nonetheless an effective way of improving the ceramic armour performance.

The effect of radial confinement in combination with adding cover plates to an Al_2O_3 ceramic backed by steel, was studied by Anderson and Royal-Timmons [38]. Four target setups were investigated, as illustrated in Figure 5.1. The DOP of the tungsten long rod penetrator into the steel backing was used as a measure of ceramic performance. The experimental tests showed, in line with the expectation from the explanation given above and in Section 4, that the radial confinement improved the performance of the ceramic. Furthermore, the ceramic targets with an additional steel cover showed an even higher performance (the effect of the additional steel in the targets was taken into account). The performance of the ceramic also depended on the hardness of the steel front cover plate. A harder steel front plate gave better ceramic performance compared to one made of a softer steel. Furthermore, a slightly better ceramic performance was observed for one hard steel front plate compared to two similar plates. Thus, there is likely to be an optimum thickness of the front cover.

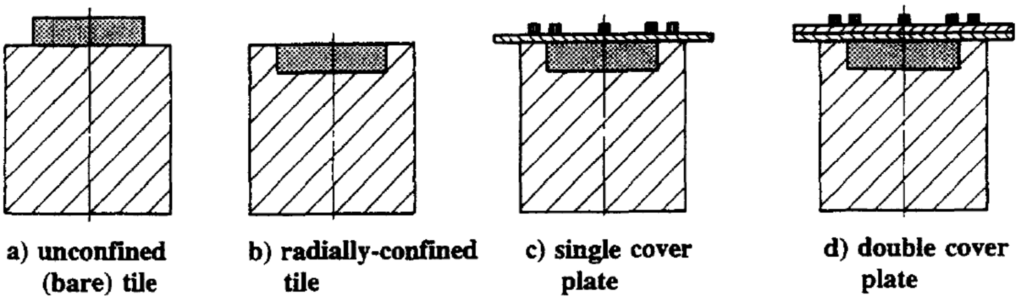

Figure 5.1 Different test setups; no radial confinement, radial confinement, and combined radial confinement and front cover. Reprinted with permission from Anderson and Royal-Timmons [38].

The positive effect of a front cover on the ceramic is supported by long rod impact tests performed by Holmquist et al. [39]. They found an increase in the transition velocity for radially unconfined SiC ceramic, from 822 m s^{-1} to 1538 m s^{-1}, when a copper buffer disc was added to the front of the ceramic. They also performed numerical simulations using the finite element method (FEM), in order to study, not the effect of the thickness of the front cover, but the size/width of the cover. The simulations showed that a smaller width of the cover disc (such that the ceramic is only protected in the region where the long rod hits) gave a slightly higher transition velocity than a full cover plate. The simulation showed that this was a result of the outwards radial flow of debris from the impact region in the fully covered ceramic. This effect was, however, not observed in the experiments. Furthermore, from a practical perspective, it is not trivial/possible to cover only a small region on the ceramic tile in a SAPI insert plate, since the plate should protect a larger area. It is nonetheless worthwhile to keep in mind the possible negative effect of radial flow of the debris.

5.3 Impact with regular projectiles

Radial confinement

Ceramic armour systems for personnel protection (SAPI plates) are not designed to resist impact by long rods. They are primarily designed to protect against threats from rifles. Thus, it is interesting if the positive effect of radial confinement is also observable for rifle threats. Several such experiments have been conducted, and the general result is, not surprisingly, that the positive effect of radial confinement is also true for regular projectiles at realistic impact velocities.

In a DOP study on the effect of the confinement cylinder material, using B_4C ceramics and a 7.62 mm AP projectile at velocities up to 820 m s^{-1}, Savio et al. [40] found a 19 % decrease in the penetration depth with an aluminium alloy compared to no confinement. When using a steel radial confinement, the decrease in penetration depth was 34 % compared to no confinement. This increase in B_4C performance with steel compared to aluminium was attributed to the degree of reflection of stress waves in the boundary between the ceramic and the confinement material. The transmission and reflection of stress waves is determined by the acoustic impedance[2] of the two materials. If the acoustic impedances of the two materials are identical, a stress wave is fully transmitted at the boundary. However, if the two materials have different impedances, a part of the stress wave is reflected back into the ceramic at the boundary. The reflected part of the stress wave is increasing with higher impedance differences. For the extreme case, where there is no confining material, all of the stress wave is reflected back into the ceramic. The difference in acoustic impedance is larger between B_4C and aluminium, than it is for B_4C and steel, giving more stress wave reflection when using aluminium radial confinement.

Confinement pre-stress

As discussed above, a better match in the acoustic impedance of the ceramic and the radially confinement material gives better performance of the ceramic (due to less stress wave reflection from the edges of the ceramic). Adding an additional compressive stress to the ceramic can further improve the performance of the ceramic. In a series of experiments, Sherman and Ben-Shushan [29] and Sherman [41], studied the ballistic performance of square Al_2O_3 tiles with no confinement, with confinement by a steel frame (no confinement stress), and with applied compressive biaxial pre-stresses of 130 MPa and 200 MPa. The experiments showed a positive effect on the performance of the ceramic when confined - the number of radial cracks in the ceramic was unchanged, but the permanent deformation of the backing plate was lower with confinement. However, the improvement for the pre-stressed confinement was higher, especially when a steel backing plate was employed. For thicker ceramic tiles (8 mm and above) backed by a thick steel plate, no cone cracks were observed and the number of radial cracks were lowered. When a thinner steel backing plate was employed, the damage to the ceramic increased. This was due to buckling of the pre-stressed ceramic tile when the backing plate was too thin. This was also supported by results from an aluminium backing plate, where the damage to the ceramic increased further, and finally for an UHMWPE backing plate where the damage to the ceramic was extensive. The main conclusions were that both confinement and biaxial pre-stressing of the ceramic have positive effects, resulting in improved performance. However, if the backing material has a low bending rigidity, or the backing plate is too thin, the positive effect of pre-stressing diminishes. This is a result of bending of the ceramic during impact (due to the formation of radial cracks on the backside of the ceramic) if not supported sufficiently. For thick ceramic tiles, this is not the case, since the formation of radial cracks is less pronounced in thick ceramic tiles, as discussed in Section 4. The load required for formation of radial cracks can also be calculated on the basis of ceramic thickness, backing material and confining pressure, of which an example is shown in Figure 5.2. Here, it is clear that radial crack formation takes place at higher loads when employing a steel backing with confinement pressure, compared to an aluminium backing and no confinement pressure. Furthermore, when the initiation load increases, a larger number of radial cracks are formed since one radial crack will only unload a limited amount of stress.

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[2] Longitudinal acoustic impedance is given by $Z = \sqrt{\rho E}$, where ρ is the density and E the elastic modulus.

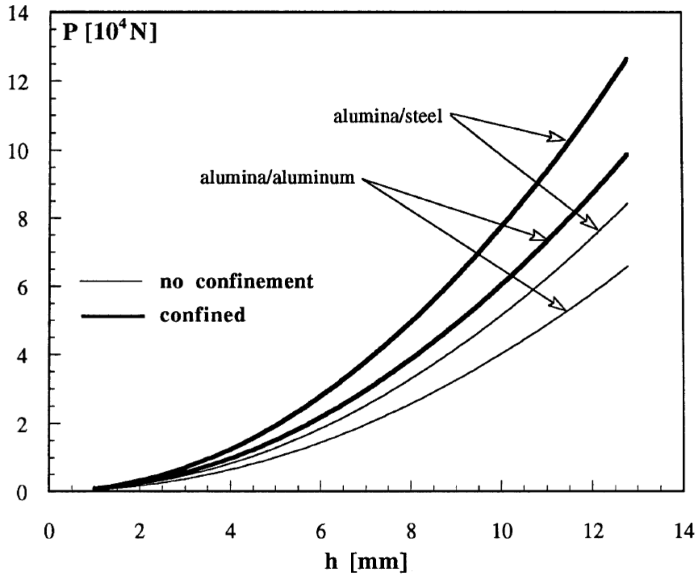


Figure 5.2 Predicted load for initiation of radial cracks on the backside of an Al_2O_3 tile. Steel backing and confinement increases the initiation load, compared to aluminium backing and no confinement. The confinement pressure used here was 200 MPa. Reprinted with permission from Sherman and Ben-Shushan [29].

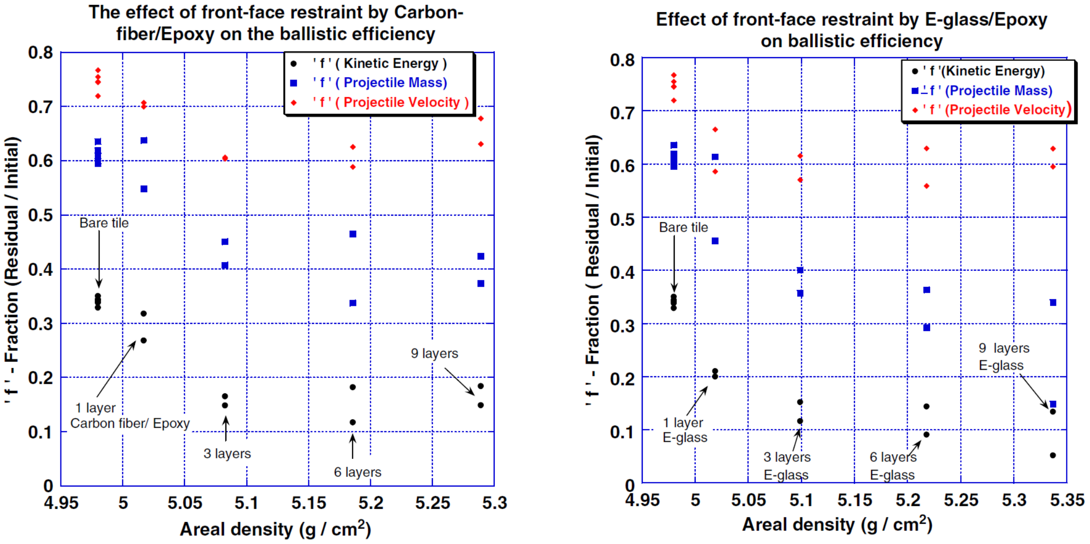
5.4 Covering with fibre-composites

Effect on single-hit performance

Using a metallic cover is not necessarily the most weight-efficient method to constrain the ceramic tile. By using strong fibres in uni-directional (UD) sheets or as woven fabrics in a composite, it is possible to constrain the ceramic with a lower added mass. Several materials have been used to cover the ceramic tiles. Nunn et al. [20] studied the effect of adding front-layer sheets of UD carbon fibre composites to B_4C ceramic tiles backed by a UHMWPE-plate. There was no pre-stress in the ceramic, only the constraining effect from the composite. From ballistic impact by a 7.62 mm M61 round, they found up to 40 % increase in the V_{50} (see Section 3.2 for details on V_{50}-testing) at an increase in areal density of only 9 %. They also showed that the V_{50} increased with an increasing number of composite front layers. There are no clear conclusions as to why they found this positive effect, but Nunn et al. [20] speculate that it might be due to the lateral constraining effect on the ceramic, which could slow down the propagation of cracks.

Sarva et al. [22] are more clear on the possible reasons for the improved performance of ceramic constrained by fibre-composite materials. In the paper, they primarily discuss the effect of adding a front cover (epoxy/E-glass, epoxy/carbon fibre or titanium) to Al_2O_3 ceramic tiles without backing. For all materials, they found a positive effect of adding a front cover, as seen in Figure 5.3, and they also found an increase in energy absorption with increasing front layer thickness. However, they concluded that there is an optimal layer thickness of the front cover layer in terms of ballistic performance versus areal density. In their work, the optimal thickness was 0.75 mm (3 layers) for

12.75 mm thick ceramic tiles. A front layer of this thickness was capable of constraining the ceramic tile during the ballistic impact. From X-ray images taken during the ballistic impacts, they concluded that the positive effect of the front layers is due to a more restricted and confined flow of pulverized ceramic debris in front of the penetrator. The ceramic debris created in the impact region is restricted from flowing in other directions than towards the penetrator, which results in increased penetrator erosion. With this finding and supported by experimental evidence, they also concluded that adding a similar cover layer on the back side of the ceramic, does not give a significant additional increase in tile performance.



(a) Results for a carbon fibre/epoxy composite.

(b) Results for a glass fibre/epoxy composite.

Figure 5.3 Residual kinetic energy of the projectile after impact on Al_2O_3 targets with composite front cover. The composite materials improve the ballistic efficiency of the ceramic system at a very low increase in areal density. Reprinted with permission from Sarva et al. [22].

Some of the conclusions of Sarva and coworkers are supported by an experimental study by Reddy et al. [42], who found an increase in the erosion of the penetrator, when the ceramic target is confined on the front side by a ballistic fibre material (aramid or UHMWPE). They also found that the size distribution of the ceramic fragments changed when a front cover is added. A larger fraction of the ceramic debris was of smaller size when the front cover was added, which suggested that the ceramic in the region in front of the penetrator took part in the loading and erosion of the penetrator for a longer time period. This is supported by an experimental study performed by Tan et al. [43] on covering and radial confinement of an Al_2O_3 ceramic by aluminium or steel. They concluded that the increase in performance of the covered ceramic was due to an increased interaction between the penetrator and the ejected ceramic debris, since the cover plate restricted debris from moving outwards anywhere else than against the penetrator.

The statement that having a back cover on the ceramic does not add any additional positive effect in performance may be supported by the results in the experimental setup of Sarva et al. [22]. However, the works of Sherman presented earlier, state that the stiffer the backing the better the ceramic performs. On another note, work at TNO by Carton et al. [6] have shown that whether the ceramic has a backing or not is not important when it comes to increasing the dwell time of the penetrator upon impact. Instead, they found an essentially linear correlation between dwell time and the areal density of the ceramic/composite system, more or less irrespective of ceramic and composite type as long as the ceramic was harder than the penetrator. However, in real life situations, where the projectile has to be fully stopped for a protective measure to be successful, then a backing capable of absorbing the projectile kinetic energy is needed.

Öberg et al. [44] have studied the effect on ballistic performance of having a 0.8 mm carbon fibre/polyethylene terephthalate (PET) composite backing on thin 2 mm Al_2O_3 tiles impacted by steel spheres. The energy absorption of a bare tile was compared to ceramics having no, weak and strong adhesion to the composite backing. The findings from the experiments, as shown in Figure 5.4, were that there is no difference in energy absorption between the samples with no and low ceramic/composite adhesion. However, with good adhesion the energy absorption increased by an amount that could not be explained by additional delamination energy during impact. They suggested that the better energy absorption properties were due to a larger degree of energy absorption within the composite with the increased adhesion. Whether this effect is significant for a tile thickness used in realistic ballistic protection systems is not clear, and needs more investigation.

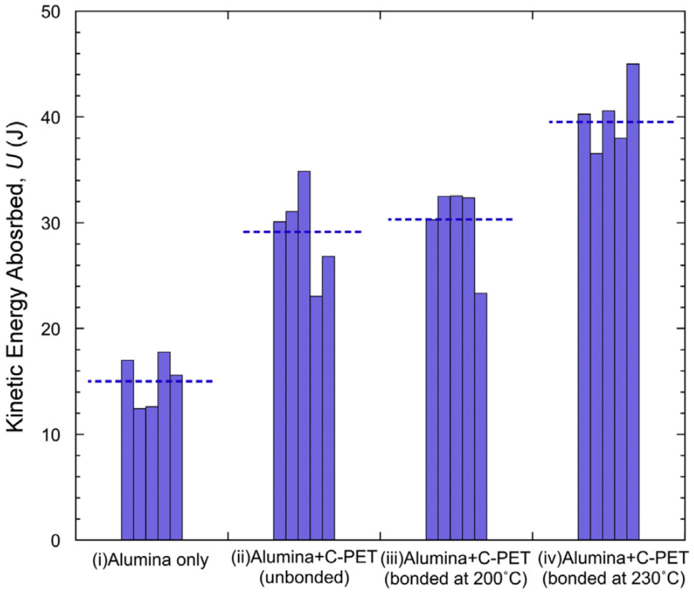


Figure 5.4 Energy absorption in ballistic experiments with thin Al_2O_3 ceramic tiles with and without carbon fibre/PET composite backing. The absorbed energy increases with increased bond strength (higher processing temperature gives higher bond strength). Reprinted with permission from Öberg et al. [44].

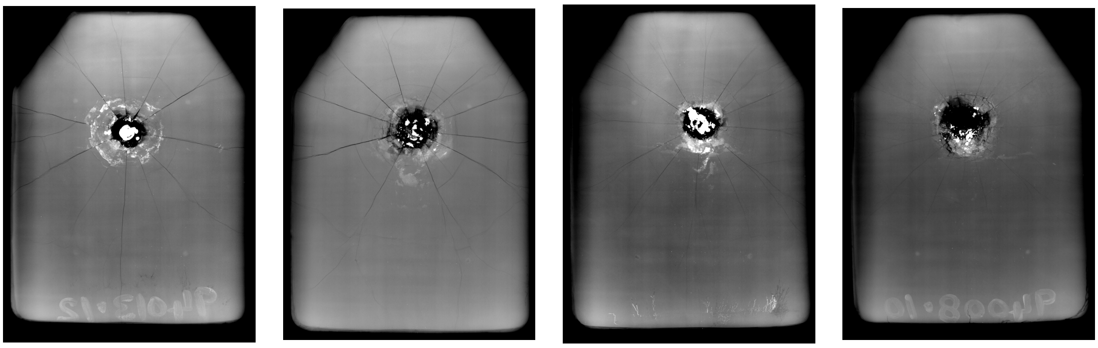
Effect on multi-hit performance

From the work presented above, it is clear that adding a cover-layer to the ceramic can improve the ballistic performance of the intact ceramic. Another effect of adding a cover is that the ceramic is to some degree kept together after ballistic impact. Clearly, the ceramic is damaged and fractured, but with the proper cover-material and adhesion to the ceramic, the integrity of the tile is partly maintained. This is an advantage for multi-hit performance. To study the effect of covering on multi-hit performance is, however, difficult due to the many different parameters that might have influence on the results. It is therefore cumbersome to obtain trustworthy data on multi-hit performance.

Horsfall and Buckley [45] have performed experiments that give some indication of the effect of covering of ceramics on multi-hit performance. They compared the ballistic performance (V_{50}) of intact Al_2O_3 with the performance of a pre-cracked Al_2O_3 tile both covered and backed by a glass fibre composite. The pre-crack was a single through-thickness crack, which was held closed by the composite cover, and the impact position of the 7.62 mm P80 (same as M61) projectile was close to the position of the crack. Interestingly, the experiments showed only a very low drop in the (V_{50}) performance of the cracked tiles of 3 %, from 764 m s^{-1} to 740 m s^{-1}. They concluded that the performance of the pre-cracked tile was almost unchanged due to the confinement by the front and back covers. The composite covers prevented the compressive stresses, created in the ceramic in the region beneath the penetrator upon impact, to be relieved.

In another study, Watson et al. [46] looked into the V_{50} performance of real SAPI-plates and compared this to national requirements. They first tested plates from six production batches and found these batches to perform from 16 % to 24 % better than requirements. Next, plates from the same batches, but with intentionally made pre-cracks in the ceramic, were tested. Thus, the ceramic tiles had clear distinct cracks that were observable in X-ray images. A decrease in performance of 7 % to 8 % was observed for the pre-cracked plates. Nevertheless, the plates still gave V_{50} performance that was 15 % higher than the requirements. To study this further, SAPI-plates which contained fine cracks in the ceramic originating from in-service use, were tested. The fine cracks were not visible on the outside of the plates, but did appear in X-ray images. As was the case for the intentionally pre-cracked plates, these latter plates gave a relatively small decrease in performance (down to 10 % to 12 % higher than the requirements). As a final test of the influence of cracks in the ceramic tiles in SAPI-plates, plates that had been rejected from the above batches due to clear damage on the outside were tested. As might be expected from the other tests, also these damaged plates were found to perform better (12 %) than the requirement level. These results show that it is difficult to define an expected lifetime for a SAPI-plate, since cracks in the ceramic is not necessarily detrimental for performance. In fact, delamination between the composite cover and the ceramic might actually have a more negative effect on the SAPI-plate performance, although this remains speculation.

Crouch [47] presented results from multi-hit testing of full-sized SAPI plates with and without cover. Tiles were tested with no cover, with a polymer film cover, and with polyester-reinforced or aramid fibre-reinforced epoxy covers. He found that the number of radial cracks increased when a cover is added to the ceramic. Moreover, the results showed that a stronger cover gives a higher number of radial cracks in the ceramic. This was attributed to an increase in hoop stress[3] in the ceramic tiles with cover. Examples of the radial cracks with the various cover types are shown in Figure 5.5. It is clear that the cracks are more visible and, hence, more open when the ceramic is not covered by a fibre-composite. For the aramid-covered ceramic tile, Figure 5.5d, the cracks are hardly visible although there are more cracks present than in the other plates.



(a) No cover. *(b) Polymer film.* *(c) Polyester/epoxy.* *(d) Aramid/epoxy.*

Figure 5.5 X-ray images of SAPI plates after impact by 7.62 mm M2AP projectile. The cracks are more visible and, hence, more open for the SAPI plates with no fibre-composite cover. The figures are adapted from Crouch [47].

The multi-hit performance was also better for the plates with fibre-composite covers. The deformation of the clay used as backing was smaller for these plate, both for the first, second and third shots. As can be seen in Figure 5.6, the cracks emanating from the impact region of both the second and third shots are essentially limited by the radial cracks formed by the first shot, which means that the radial cracks from the first impact acts as crack stoppers. From the work by Horsfall and Buckley [45] and Watson et al. [46], it is known that the performance is lower for cracked plate, but that with a strong composite cover the reduction in performance is low. The positive effect of a fibre-composite cover is then the reason why the larger number of radial cracks observed for these composite-covered plates do not result in lower performance for the second and third shots.

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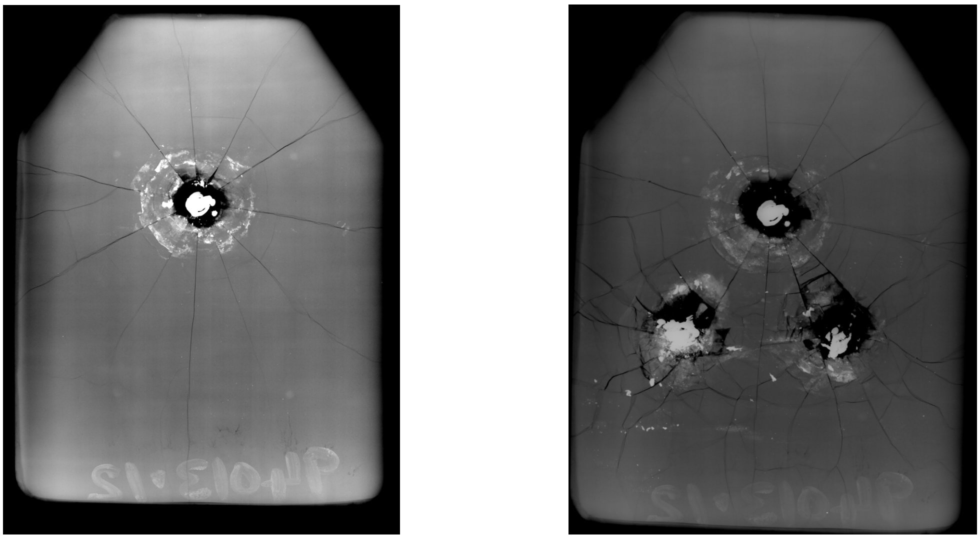
[3] Hoop stress is the stress component in the circumferential direction in cylindrical coordinates. In other words, it is the stress tangentially to both the radial direction and to the through thickness direction.



(a) Cracks in a ceramic without cover tile after one shot.

(b) Cracks in an uncovered ceramic tile after three consecutive shots.

Figure 5.6 X-ray images of the same SAPI plate after the first impact by a 7.62 mm M2AP projectile and after a total of three impacts. The cracking from the second and thirds shots is restricted by the radial cracks from the first impact. The figures are adapted from Crouch [47].

6 Effect of adhesive and interfacial bonding

The degree of adhesion and the properties of the adhesive layer between different materials in armour systems, is expected to have an effect on the ballistic performance. The amount on literature on these subjects appears to be somewhat limited, but some relevant effects are discussed in this section.

Main points on adhesive bonding and interfacial properties

- A stronger ceramic/cover material adhesive bond has a positive effect on single-hit performance.
- Higher adhesion can have a positive effect on multi-hit performance of a multi-tile armour system.
- There may be an optimal adhesive layer thickness in ceramic/cover material systems due to competing effects for thin and thick layers. A thin layer minimizes bending of the ceramic and reduces spalling, while a thicker layer distributes the impact load over a larger area and more ceramic remains attached to the adhesive.
- Adhesion can be improved by surface treatment of the ceramic.

6.1 Adhesion and bondline thickness

As discussed in Section 5.4, Öberg et al. [44] found that the adhesion between a ceramic tile and a composite cover had influence on the ballistic performance. The absorbed kinetic energy in ballistic tests was higher for a system with a higher measured ceramic/composite fracture energy of 620 $\mathrm{J\,m^{-2}}$, compared to 170 $\mathrm{J\,m^{-2}}$. This does not necessarily mean that high adhesion is always better for ballistic performance. The studied system was with a very thin (2 mm) Al_2O_3 ceramic tile, which is too weak for normal protection purposes. Another point to consider is that a strong adhesive bond could actually have a negative effect on the ballistic performance. With high adhesion, the load from the impact might be concentrated to a smaller area on the target, and not distributed over a larger area as desired. On the other side, with low adhesion the ceramic fragments from the impact may not be held in place.

Combining experiments and modelling, Zaera et al. [48] studied the effect on the ballistic performance of Al_2O_3 bonded to an aluminium backing plate. Two different adhesives, epoxy and polyurethane (PU), were employed and the bondline thickness was varied (0.5 mm, 1.0 mm and 1.5 mm). Moreover, ceramic tiles with three different thicknesses were used. Their main finding was that the kinetic energy absorbed by the ceramic/aluminium system decreased with increasing adhesive layer thickness independent of the ceramic tile thickness. For the 4 mm and 6 mm ceramics, the epoxy-bonded systems performed slightly better, whereas no substantial difference between the two adhesives was found for the 8 mm ceramic. From the modelling it was found that a thicker adhesive bondline resulted in a larger area of plastic deformation in the aluminium backing, as shown in Figure 6.1. This behavior is positive with respect to energy absorption. Unfortunately, the thicker adhesive also resulted in earlier shattering of the ceramic, a negative effect that results in poorer performance for the thicker adhesive. It was suggested that the better performance when using epoxy for the thinner ceramic tiles, was related to the impedance and the elastic wave speed of the adhesive. Both the wave speed and the impedance is higher for epoxy than for PU and hence closer to the values for the Al_2O_3. The better impedance match between epoxy and Al_2O_3 results in lower tensile stresses on the backside of the ceramic, and the higher wave velocity results in faster transmission of the compressive load through the adhesive and into the aluminium backing.

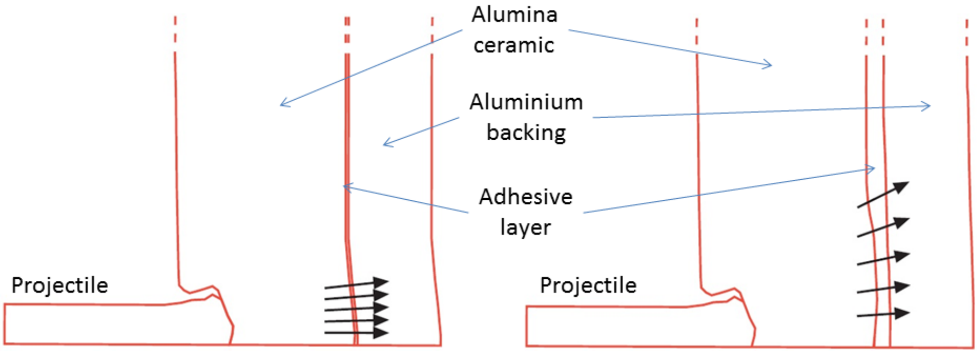


Figure 6.1 Load transmission zone for a thin (left) and a thicker (right) adhesive layer. Reprinted with permission from López-Puente et al. [49].

In a continuation of the above mentioned study, López-Puente et al. [49] found that there may be an optimal thickness of the adhesive layer. For armour systems of either 6 mm or 12 mm thick Al_2O_3 tiles bonded to an aluminium backing by epoxy, they found that the best performance was with an adhesive layer thickness of 0.3 mm. They suggested that an optimal thickness may be due to three effects. First, as mentioned above, the thicker adhesive allows for activation of a larger area of the backing material, Second, a thicker adhesive is subjected to lower shear stresses, which means that the ceramic remains attached to the backing layer. Third, a thinner adhesive prevents the bending of the hard, brittle ceramic and thus reduces the spalling of the ceramic. For the studied system, the adhesive thickness of 0.3 mm then gave the best balance between the above mentioned effects.

Clearly, the choice of adhesive and the bondline thickness may have effect on the ballistic performance of ceramic armour. It is, however, not obvious whether the strength of the adhesive bond has a significant influence on the performance or not. Harris *et al.* presented experimental results [50], that suggested that higher adhesion has a positive effect on multi-hit performance of a larger scale ballistic system. They found the delamination between Al_2O_3 tiles and a backing material to be decreased with a stronger adhesive bond. Whether a smaller degree of delamination had a negative effect on the performance of one hit was unclear (as a lower degree of delamination might result in activation of a smaller area of the backing material).

6.2 Multi-hit

Another topic discussed in the work by Zaera et al. [48], was multi-hit capability in a multi-tile configuration with an adhesively bonded ceramic/backing plate system. They found that although a thin adhesive layer resulted in the best performance for an individual tile on the first impact, a lower degree of fragmentation and damage was observed in adjacent tiles for a thicker adhesive layer. This supports having a thicker adhesive layer for increased multi-hit performance of this type of system. The adjacent tiles are then more able to withstand a second impact.

There are also other parameters that can be adjusted to obtain better multi-hit capability. One of these is the tile size in a multi-tile configuration used in, for instance, vehicle protection. If the individual tiles are too large, the multi-hit performance is decreased [51], since a larger structural area is damaged on the first impact. Thus, for very large individual tiles, the unprotected area is large. The solution is to use smaller tiles - most often of hexagonal shape. The advantage with hexagonal tiles is that the distance from a centre impact to the nearest edge is somewhat larger than for square tiles. This distance is important since it takes longer time for the stress wave to reach the edge and to return as a release wave to the impact point. However, this also suggests that the individual tiles should not be too small, in order not to lose the protective capabilities of the individual intact tiles.

6.3 Surface treatment

Several surface treatments have been employed to improve the adhesion to Al_2O_3, SiC and B_4C ceramic surfaces. These treatments include methods such as grit-blasting, abrasion, plasma, laser ablation, sol-gel and silane treatments. For a thorough discussion on the topic of adhesion to armour ceramics, the reader is referred to references CERAMBALL [12], Lausund [52], Lausund et al. [53].

6.4 Interlayer

In a more recent study, Tasdemirci et al. [54] studied the effect of three types of interlayer between an Al_2O_3 ceramic tile and a glass fibre composite backing plate; rubber, Teflon and aluminium foam. They found that the damage in the ceramic was affected by the choice of interlayer. For rubber, the damage in the ceramic was more localized around the projectile, while a wider damage zone was observed with Teflon and aluminium foam. They concluded, in line with Zaera et al. [48] and López-Puente et al. [49], that a larger damage zone is beneficial for activating a larger area of the backing plate. Another difference between rubber and Teflon interlayers was that the ceramic broke into relatively large pieces upon impact when a rubber interlayer was used, whereas a Teflon interlayer resulted in smaller ceramic pieces i.e. more ceramic fragmentation.

7 Conclusion

In this report, ceramics that are employed in armour systems have been discussed on the basis of a literature study. The most commonly used armour ceramics have been presented, as well as some of the most important material properties of armour ceramics, such as hardness and fracture toughness. Moreover, the typical construction of a hybrid armour system for personal protection has been presented.

There are several methods for testing of the ballistic performance of ceramics. One main category of tests is used to test complete protection systems (containing a ceramic tile). For example, ballistic insert plates are often tested in combination with a soft vest, and with a clay backing, to verify if the given requirements for the whole protection system are fulfilled. Other tests may be used to determine the performance of the individual parts of a hybrid armour system. From a scientific perspective, it is important to know the properties of the individual materials, and to understand how they fail when impacted. Examples of test methods for this purpose are the V_{50} and depth of penetration tests.

In the initial phase of projectile impact of a ceramic, the ceramic remains intact due to the high intrinsic compressive strength, whereas the projectile is blunted, fractured and eroded. This phase is called the dwell time. However, as tensile and shear stresses build up on the backside of the ceramic and in the region outside the projectile/ceramic contact zone, radial cracks and cone cracks initiate and propagate through the ceramic. Simultaneously, micro-cracks form in the ceramic directly underneath the penetrator due to the high stresses. When fractured, the ceramic is less capable of stopping the projectile, although the ceramic fragments are still active in eroding it.

When adding a cover layer to the ceramic, the ceramic fragments are forced to flow in the direction of the projectile, and the overall performance of the hybrid protection system is increased. Furthermore, a cover layer keeps the ceramic fragments in place, thus the integrity of the ceramic is partly retained, and the multi-hit performance of the hybrid system is increased. The ceramic performance can be improved further by adding a circumferential pre-stress. This is unfortunately difficult to achieve with the current production techniques. However, there appears to be promising effects from tailoring the adhesive strength between the cover layer and the ceramic, both in terms of single-hit and multi-hit performance.

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