1

INTRODUCTION

It will not be surprising to the reader that over the last century it has been increasingly necessary to apply thicker armour plates to armoured fighting vehicles to provide protection against new gun and projectile designs. Consequently, the design of a modern armoured fighting vehicle has evolved so that it will typically have 40–50% of its weight accounted for by protection. But as the weight of the armour increases, maintaining mobility and stealth, and deploying these vehicles over large strategic distances becomes increasingly problematic. Furthermore, armed forces would prefer to deploy armoured fighting vehicles to the battlefield by air—simply because of speed. This factor alone has led to a number of design constraints that have been placed on future armoured fighting vehicles intended to reduce their bulk and weight.

At the same time, we are finding that weapons that are used to attack armoured vehicles have developed to the extent that:

- some of the more advanced shaped-charge warheads can penetrate well over a metre of rolled homogeneous armour (RHA);
- kinetic-energy long-rod penetrators are getting longer and faster and as a consequence are able to penetrate ever-greater depths of RHA; and
- explosively formed projectiles and shaped-charge jet warheads are being delivered to their target in a variety of ways to exploit zones on an armoured vehicle that have traditionally been less well protected—such as the roof.

Therefore it is desirable to ensure that universal protection is provided against all of these threats all around the vehicle—this adds weight!

There was little improvement in the performance of armour materials between and during the two world wars and just after WWII when armoured vehicles used steel as the main armour material. Apart from the occasional use of face-hardening and the rare application of dual hardness plates that improved performance of the armour, the main improvement to resisting perforation was offered by increasing the thickness of steel. Figure 1-1 illustrates how this protective performance improved.

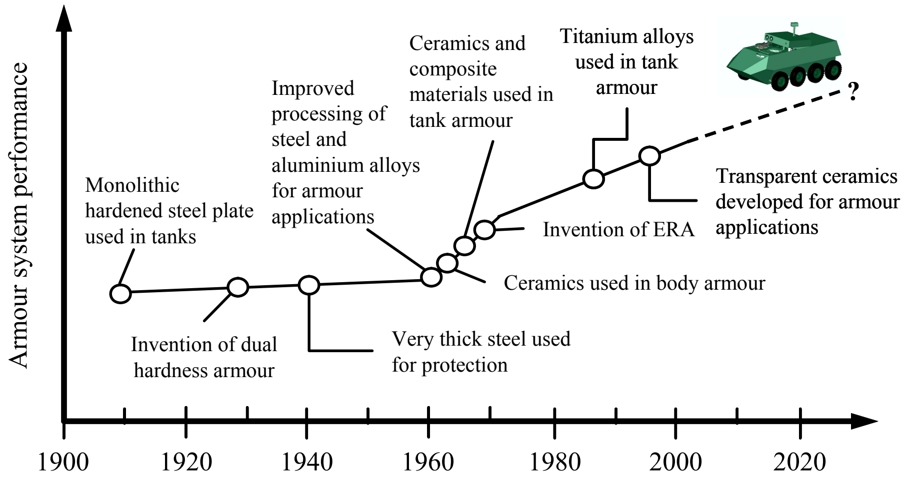


Figure 1-1: Armour development timeline.

So, by WWII, tanks such as the Soviet KV of 1941 had steel plates 75 mm thick and the German Tiger of 1944 had a 150-mm plate at the front of its hull and 185-mm plate at the front of its turret [1]. However, with the introduction of advanced processing techniques, explosive-reactive armours, composite materials, and ceramic materials around 30–40 years ago, the performance of armour systems improved dramatically (see Figure 1-1). These developments were key to the drive for reduced armour weight.

Further enhancements in performance were made by studying the penetration mechanisms of projectiles in armour materials using high speed diagnostic equipment such as flash X-ray and high-speed photography. System design was enhanced by the development of analytical and computational codes that could also be used to study penetration mechanisms. These codes enabled engineers to test different armour designs and conduct optimisation studies without even leaving the office. Consequently, using both of these experimental and computational tools, armour solutions were discovered that employed two or more materials that, when combined, provided advantageous properties to resist penetration, delay failure and improve multi-hit capability.

Much of this development in armour performance went hand-in-hand with weapon development but meant that lightweight vehicles could offer the same, if not better, protection than their heavier predecessors. But this didn't sound the death knell of metallic armour materials. Indeed, much armour development that has occurred has relied on using materials and systems applied to existing metallic hulls where the metallic hull has provided the last line of defence and an integral part of the complete armour solution.

The current use of ceramic materials for armour on vehicles and in body armours should be no surprise to the reader who is familiar with their mechanical properties as they mostly possess relatively high compressive strengths when compared to steels, titanium, aluminium alloys, and the cores of all armour-piercing projectiles. Furthermore they possess relatively low bulk densities—at least half that of steel and therefore quite large thickness of these materials can readily be used to provide the required level of protection whilst maintaining a moderate armour weight. Of course, there are occasions when ceramic materials are an inappropriate choice for armour systems because of their brittleness (and occasionally their cost) and therefore the reader should be under no illusion that they will provide the definitive means of protection.

This book intends to introduce the main lessons learnt in the application of ceramic armour technology over the years and to provide the student or engineer the necessary background information to implement and develop a ceramic-armour system for their application. We begin by looking at some fundamental armour design concepts.

1.1 DISRUPTOR OR ABSORBER?

Fundamentally, there are two types of armour that are available to the armour designer: passive and reactive. Passive systems work by stopping the projectile by the material properties of the armour components alone. In contrast, reactive systems generally work by the projectile incurring a kinetic response in the armour material, the nature of which intends to reduce the lethality of the projectile by disruption or deflection. Ceramic materials tend to be used in passive armour systems.

Ideally, the armour system should be as effective and as lightweight as possible. Therefore a desirable system would employ materials of low density and high resistance to penetration. The choice of materials used in passive armours depends on what the design engineer wishes to achieve. Armour materials can be divided into two different categories that depend on their material properties and the way in which they deal with the energy of the projectile. Armour materials tend to be either energy 'disruptive' in nature or energy 'absorbing'. Disruptors tend to be made from high-strength materials such as high-hardness steels and ceramic materials. The purpose of these materials in a multi-layered armour construction is to fragment the incoming projectile or rapidly erode it. In other words, the kinetic energy of the projectile is dispersed by the armour material by fragmenting the projectile and redirecting the energy of the resulting fragments away from the protected structure. An absorber on the other hand works to absorb the kinetic energy of the projectile through large amounts of plastic deformation thereby converting it to a lower form of energy such as heat. Most armour systems are optimised to both 'disrupt' and 'absorb' the kinetic energy of the incoming threat. Figure 1-2 shows a section through a T 80's glacis plate that uses both 'disrupting' and 'absorbing' materials to provide protection. In this case, hardened steel is used as an outer facing to disrupt any incoming threat, although a ceramic layer may well have been used. The layers of toughened steel and glass fibre are used as an absorbing component of the armour system. The spall liner (which also acts as an 'absorber') exists to reduce the effects of any behind-armour debris that may result from an impact or perforation. This would usually be made of an aramid or glass-fibre-reinforced composite material although more recently composite materials made from ultra-high molecular weight polyethylene fibres have been used [2].

The disruptive component of an armour system is either a hard material such as ceramic or high hardness steel or a moving material such as an explosive-reactive armour plate if disruption of a shaped charge jet is the objective (see Chapter 8). The absorbing components of armour systems are generally materials that can undergo large amounts of plastic deformation before they fail. Some hard-facing disruptor materials such as ceramics or glasses are susceptible to brittle fracture and therefore it is frequently necessary to contain the material so that the fragments are retained in place after the tile has been perforated. In doing so it is possible to provide some level of multi-hit protection although performance against subsequent hits would be compromised. Other disrupting materials such as certain high-hardness steels and hard aluminium alloys plates can be susceptible to gross cracking if penetrated which means that the plate would need to be replaced although in these cases a good multi-hit capability would still be retained despite the fracture.

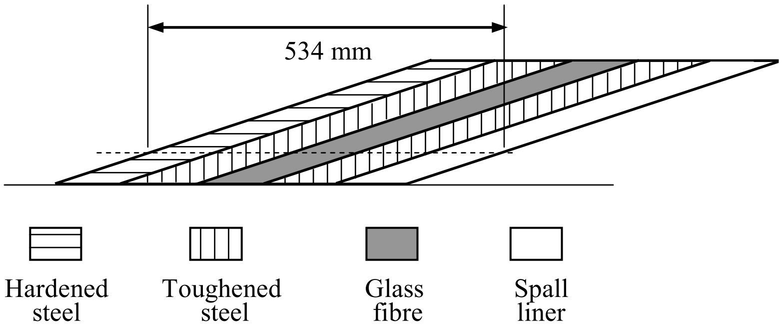
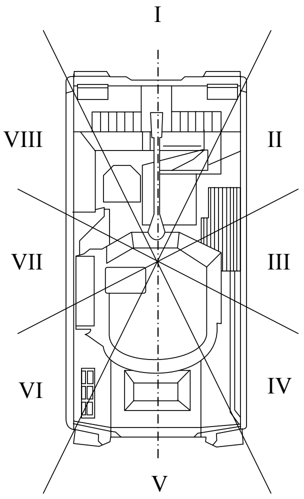


Figure 1-2: Section through a T 80's glacis plate showing the 'disrupting' and 'absorbing' materials.



Segments of 45°	
Segment	Probability of attack in segment
I	0.3406
II	0.1996
III	0.0823
IV	0.0425
V	0.0108
VI	0.0425
VII	0.0823
VIII	0.1996

Figure 1-3: The probability of attack on a specific segment from a line of anti-tank guns on an axis perpendicular to the direction of travel by the tank.

1.2 THE DISPOSITION OF ARMOUR

Frequently we find that even with modern armour systems, providing all-round protection for a person or a vehicle will result in a heavy design. Therefore choices have to be made so that the location of the armour is most likely to provide the maximum amount of protection available whilst maintaining the required amount of comfort (for personnel protection) and mobility (for vehicle protection). For example, to maximise the life-saving ability of a bullet-resistant vest, it is appropriate to provide ceramic inserts to protect the vital organs such as the heart and lungs whilst providing minimal protection for the shoulders and arms. Furthermore, we find that most protection offered by the vest is located at the front because in the majority of cases, it is the fontal area that is attacked.

For vehicle armour, similar choices have to be made. These ‘choices’ have led to the development of ‘directional probability variations’.

The term directional probability variation (or dpv for short) was first introduced as a means to assess the chance that an AFV is attacked from a particular direction. There has been several dpvs proposed for tank hulls but that due to Lt Col J.M. Whittaker, published in 1943 [3], is the best known and is based on a theoretical model.

The basic assumption of Whittaker’s model is that a tank is travelling towards a line of anti-tank guns with a constant velocity. The line of travel of the tank is straight and is perpendicular to that of the anti-tank guns and the total number of shots that can be fired at a certain aspect of a tank is directly proportional to the time that the tank presents that aspect to the gun. Additional assumptions are made about the range of the guns and their ability to fire in any direction. Whittaker's model predicted that it was more probable that a tank will be struck in a frontal segment of the vehicle as shown in Figure 1-3.

Despite a rather simple model of a tank approaching a line of anti-tank guns at constant velocity, analysis of tank casualties in North West Europe during World War II showed that Whittaker's theory fitted the battle data reasonably well. After the war, an important lesson was drawn that the weight of armour should be more concentrated at the front of the AFV.

How well the lessons learnt from this model fit with today's AFV design is questionable. This is mainly due to the variety of mechanisms that are now available to deliver anti-tank shaped-charge warheads to the target. Other factors such as the nature of the conflict and the speed and technological superiority of the attacking force will affect the chance of a hit in a particular segment. For example, subsequent battle data from the 1991 Gulf War has suggested that the number of hits on an Iraqi AFV was more evenly spread around the azimuth [4]; 70% of the hits that were assessed by this work were from shaped-charge type warheads with only 20% of the hits being from a KE type round. Furthermore, 77% of the hits were on the turret although it is noted that the most likely reason for this is because the majority of Iraqi MBTs were located in defensive trenches so that the hulls were not exposed to direct hits. The evidence suggests that we can no longer rely on Whittaker's initial concept for AFV design but rather a more evenly distributed system of protection to defeat the large variety of munitions and their delivery method is required. Thus, it is desirable to use the lightest and most ballistically efficient armour systems and materials as possible.

1.3 WHY CERAMIC?

The term 'ceramic' comes from the Greek word *Keramos* which literally means 'burnt things' which typifies the way that we produce ceramic tiles for armour systems today. A more complete definition of a ceramic is a *solid compound that is formed by the application of heat, and sometimes heat and pressure, comprising at least one metal and non-metallic elemental solid*. The raw material for ceramic production is extracted from the earth and then processed. The most commonly extracted material is clay that has the ability to absorb water and thereby become malleable and easily shaped into bricks, tiles, cups, plates, and so on. However clays in their final form (after firing) do not have sufficient mechanical properties to be useful as armour. Bauxite is another commonly extracted mineral and contains mixtures of oxides of aluminium, silicon, and iron. This mineral can be refined to produce the base ceramic powder of aluminium oxide (alumina). Table 1-1 lists the typical material properties of some ceramics that have been used in armour applications.

Because of their hardness, ceramics are principally used in *disrupting* the incoming projectile by inducing fracture or erosion. As can be seen from Table 1-1, their hardness values are higher than all bullet cores in existence—and all non-ceramic armour materials. The hardest bullet core is made of tungsten carbide with hardness values typically of 1,200–1,550 HV. Protecting against these bullets requires non-oxide ceramics such as silicon carbide, which exhibit even higher hardness values. Combined with their relatively low density, ceramic materials can provide a weight-efficient (but sometimes costly) means of protecting against small-arms ammunition as illustrated in Figure 1-4. The areal density is the mass per unit area (see Chapter 4) of system required to defeat the 7.62-mm armour piercing (AP) round and reduces as the hardness of the ceramic increases and a composite material backing is introduced. Their high hardness and low density also make them very attractive materials to use to provide protection against the wide variety of threats discussed in Chapter 3. With densities as low as 2.5 g/cc this means that a large areal coverage can be achieved for minimum mass making them a popular choice of materials to use in body armours, aircraft armour, and AFV armour where reduced weight is important. Figure 1-4 also reveals another facet of ceramic materials in this application: they are always used in conjunction with some form of backing material. We will discuss this again in Chapter 6 when we look at defeat mechanisms.

Table 1-1: Material properties of some ceramic armour materials.

	Alumina (high purity)	**Silicon carbide**	**Titanium di-boride**	**Boron carbide**
Bulk density (kg/m^3)	3,810–3,920	3,090–3,220	4,450–4,520	2,500–2,520
Young's modulus (GPa)	350–390	380–430	520–550	420–460
Poisson's ratio	0.22–0.26	0.14–0.18	0.05–0.15	0.14–0.19
Hardness (HV)	1,500–1,900	1,800–2,800	2,100–2,600	2,800–3,400
Fracture toughness ($MPa.m^{1/2}$)	3–5	3–5	5–7	2–3

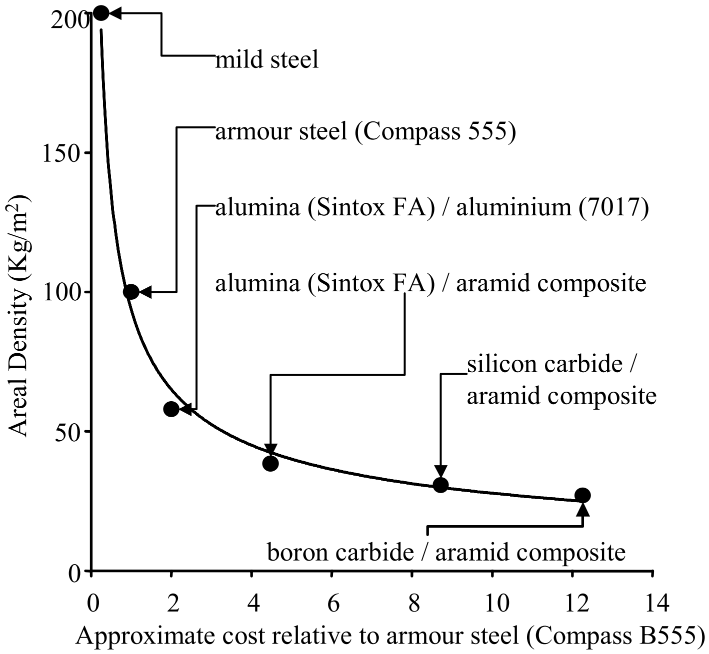


Figure 1-4: Performance versus cost relationship for armours to defeat 7.62-mm NATO AP ammunition; cost relative to armour steel (B555); adapted from Roberson [5].

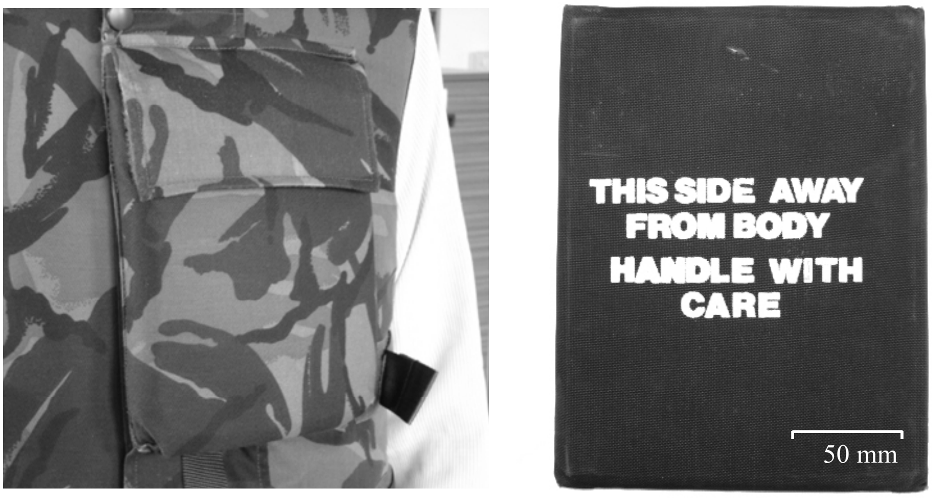


Figure 1-5: Combat Body Armour (CBA) showing the pocket for the ceramic plate insert (left) and a typical ceramic plate insert (right).

1.4 APPLICATIONS

The first realisation that a hard facing would improve ballistic performance was in 1918 when the physicist Major Neville Monroe Hopkins experimentally observed that 0.0625 inches of hard enamel on the impact-face of steel increased protective ability [6]. However it was not until the 1960s that this knowledge was exploited with the development of the first ceramic-faced armour.

The first real use of ceramic-armour technology was in US helicopters during the Vietnam conflict where low-level sorties made the helicopter and crew vulnerable to small-arms fire. Therefore, in 1965 the first ceramic-based aircrew body armour vest was manufactured [7] as this was the most weight-efficient means of providing protection. Also in 1965, the UH-I ‘Huey’ was fitted with a ‘Hard Faced Composite’ (HFC) armour kit used in the armoured seats for the pilot and co-pilot. The seats provided protection against 7.62-mm AP ammunition on the seat bottom, sides, and back due to the use of a boron carbide face and fibreglass backing [6]. In 1966, the first monolithic ceramic body armour vest was issued to the helicopter crews along with other protection improvements including the use of airframe-mounted armour panels. It has been estimated that, between 1968 and 1970, these improvements in aircrew armour reduced the number of non-fatal wounds by 27% and fatalities by 53% [6].

Since these early years, ceramic armours have been used extensively in protective design and have not just been used in helicopters but also in VIP limousines, logistic vehicles, armoured personnel carriers, infantry fighting vehicles, main battle tanks, and transport aircraft and they have been widely used in personal protection as body armour.

Body armour needs to be lightweight, comfortable, and suitably flexible and therefore ceramic materials cannot provide universal protection all around the body. Of course, ceramic materials can often provide a relatively lightweight solution for protecting critical organs such as the heart and lungs and therefore almost universally body armours will use a ceramic-plate insert of some kind. Recently there has been a development that veers away from the traditional methods of using ceramic inserts and instead uses a matrix of ceramic discs that are attached together to provide armour that resembles fish-scales. This concept is not a new idea for body armour and an experimental version had been developed towards the end of WWI using overlapping scales of helmet steel [8]. The matrix of ceramic discs that is used in modern systems is attached to fibre-composite materials and, unlike the solid tile inserts, allows some degree of flexibility.

One of the first UK examples of body armour that included the operational employment of ceramic materials was used during the Falklands

War when sets of 'Noroc I Armor Systems' manufactured by the Norton Company of Worcester, Massachusetts, were deployed during 'Operation Corporate'. These systems consisted of boron-carbide (a very hard and low-density ceramic) facing and a reinforced plastic laminate backing to act as the absorber [6]. Around about that time, the first mass-produced body armour using ceramic plates was introduced in Northern Ireland. The baseline soft armour, known as Combat Body Armour (CBA), consisted of a nylon-and-aramid-fibre-composite construction to which 1-kg ceramic-faced aramid-fibre-composite plates could be added to provide protection to the heart and major organs against high-velocity rifle bullets (see Figure 1-5). The ceramic used was aluminium oxide. Later, Enhanced Body Armour (EBA) was introduced consisting of boron-carbide tiles and a 'blunt-trauma' pack to provide protection against 12.7-mm calibre bullets. Blunt trauma occurs when the armour is not perforated but the momentum transfer of the impact causes large deformation in the backing layer leading to bruising, serious injury to major organs, or even death.

Unlike body armour, vehicle armour is not constrained by the need for flexibility however; multi-hit capability and reparability are commonly desired attributes. Early uses of ceramic materials included embedding ceramic spheres into the front part of turret castings of Soviet MBTs to provide deflection and erosion of armour-piercing shot. This integration exercise continued with some T 72 and T 80 MBTs. However, most ceramic systems have been applied as an appliqué kit—that is, an armour system that can be attached to the vehicle's hull. These appliqué kits consist of ceramics used in conjunction with other layers of materials that are usually unseen to the user. One such example is the LAST® system (Light Appliqué System Technique) that has been deployed by US Marines. The LAST® armour system consists of six-sided ceramic-armour modules which are fitted to a vehicle's hull with pressure-sensitive adhesive. Tiles can be stacked to improve the protection level and a ballistic cover can then be applied for signature management. Similar examples have been developed that use Velcro® hook and loop fasteners to attach ceramic tiles to the sides of vehicles—with the intention of reducing the burden of applying the armour system in theatre.

1.5 SUMMARY

Ceramic materials make excellent 'disruptors'—mainly because of their high hardness coupled with their low density that enables them to be used in a wide variety of applications with a relatively small weight penalty when compared to other armour materials such as steel. However, they are naturally brittle as indicated by their low fracture toughness values and consequently their multi-hit capability is limited. Since the 1960s they have become more commonly used for the design of protective systems for personnel and vehicles and in the past 20 years they have been adopted for use in UK body armour and vehicles. However, ceramic materials are, by their very nature, incapable of withstanding significant structural loads and therefore all ceramic armours are parasitic in nature.

ENDNOTES

[1] R.M. Ogorkiewicz, *Technology of Tanks*, Jane's Information Group, Coulsdon, ISBN 0-7106-0595-1, (1991).

[2] J. Beugels, "Lightweight high performance Dyneema spall liners in armoured military vehicles", *Proceedings of the Lightweight Armour Systems Symposium*, Cranfield University, Shrivenham, OXON, UK, 3–5 October (2001).

[3] R. Gye, *Tank Armour Distribution Theory*, Operational Research Group (Weapons and Equipment), Ministry of Supply, Report No. 362, (1948).

[4] M. Held, "Warhead distribution on main battle tanks in the Gulf War", *Journal of Battlefield Technology*, **3**, (1), March (2000).

[5] C. Roberson, "Ceramic materials and their use in lightweight armour systems", *Proceedings of the Lightweight Armour Systems Symposium*, Cranfield University, RMCS, Shrivenham, OXON, UK, 28–30 June (1995).

[6] S. Dunstan and R. Volstad, *Flak Jackets: 20th Century Military Body Armour*, Osprey Publishing Ltd., London, ISBN 0-85045-569-3, (1984).

[7] R.K. Bart and J.C. Lindberg, "Ceramic bodyguards", *Advanced Materials & Processes inc. Metal Progress*, **9**, pp. 69–72, (1987).

[8] R.F. Rolston, E. Bodine, and J. Dunleavy, "Breakthrough in armor", *Space / Aeronautics*, pp. 55–63, July (1968).