CHAPTER 4

BALLISTIC RESISTANCE OF BODY ARMOR / STAB RESISTANCE OF PERSONAL BODY ARMOR

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ABSTRACT

This chapter will examine the mechanics and materials of body armour in military, police and some security related applications to protect the wearer from penetrative threats. These threats will include battlefield threats such as shell fragments and high velocity bullets, and threats to law enforcement personnel such as handgun bullets and knives. Regardless of whether the threat is a high velocity bullet, or a knife, the essential requirements of body armour are the same; first an interaction must be established to capture the projectile and extract its kinetic energy; second this energy must be dispersed without undue damage to the armour or wearer. Both these aims need to be achieved without significant rearwards protrusion into the wearer. In addition to these protection requirements it is also clear that the armour must be as comfortable as possible and reasonably light. This chapter reviews some of the approaches used to provide protection based on the all these needs.

KEYWORDS

Body armour

Ballistic fabric

Textile armour

Ceramic armour

Bullet resistant

Stab resistant

1. INTRODUCTION

Body armour has been a feature of soldier's personal equipment since the earliest periods of organised warfare. The first records of armour date back to the third millennium BC but there is evidence of offensive weapons in the eighth millennium BC (Hackett 1989), so it is likely that the history of armour is of similar antiquity. Although this development process was almost purely empirical, the vast experience gained over thousands of years led to a variety of highly effective armour systems. Modern developments such as high strength synthetic materials have built upon this to develop systems which protect wearers against bullets, shell fragments or knives. As a result of these developments body armour is now an accepted part of everyday wear for both military and police personnel.

This chapter will examine the mechanics and materials of body armour in military, police and some security related applications to protect the wearer from penetrative threats. These threats will include battlefield threats such as shell fragments and high velocity bullets, and threats to law enforcement personnel such as handgun bullets and knives. Regardless of whether the threat is a high velocity bullet or a knife, the essential requirements of body armour are the same; first an interaction must be established to capture the projectile and extract its kinetic energy; second this energy must be dispersed without undue damage to the armour or wearer. Both these aims need to be achieved without significant rearwards protrusion into the wearer. In addition to these protection requirements it is also clear that the armour must be as comfortable as possible and reasonably light. This chapter reviews some of the approaches used to provide protection based on the all these needs.

2. INJURY MECHANISMS

To understand how armour functions, it is first necessary to look at the injuries which the armour seeks to prevent. The human body is not designed to resist deeply penetrative threats as these are not common in nature so lethal injuries can result from relatively low energy penetrative impacts. In English law a kinetic energy of just over 1J is taken as the lower limit for lethality (Moore v Gooderham 1960 3 All ER 575; [1960] 1 WLR 1308), although for military purposes it is accepted that 80J are required to achieve a high probability of incapacitation from a small projectile (Cooper 1997). High velocity threats carry the additional probability that the very rapid transfer of energy during deep penetration produces a large temporary wound cavity with extensive tissue damage.

Conversely the body is quite well protected against blunt impacts with the most sensitive organs lying beneath the skull or the rib cage. A soccer ball may have a kinetic energy approaching 200J and yet is accepted as relatively benign. For entirely blunt impacts it is not clear that energy criteria are applicable as it is the induced acceleration which becomes the lethal mechanism. In falls and car accidents the human body has been shown to be capable of withstanding up to 40 gravities ($\approx 392 ms^{-2}$) (Cooper 1997) which can equate to velocity changes in excess of $50 ms^{-1}$ and associated kinetic energy in excess of 50kJ.

As a result of these observations it can be seen that armour must prevent penetration of a projectile and whilst there may be some advantage in attempting dissipate the impact energy this is not strictly necessary. As a result of this most armour is designed to be penetration resistant and does not have to absorb energy.

For soft body armour there is a concern that injuries can be caused by non-penetrating projectiles creating what is called behind armour blunt trauma (BABT) (Cannon 2001). Whilst this is a possible danger, the incidence of serious BABT is very low. Its occurrence is confined to a small number of unusual cases where the armour has been struck close to its edge or a very high energy impact has been sustained. There is some concern that the pursuit of thinner and more flexible armour may lead to a situation where the bullet is retained by the armour but the armour is so flexible that it penetrates the body in what is called a pencilling injury. This is a narrow deformation of the armour which may cause perforation of the skin and underlying tissue. Plaster casts of both a ‘normal’ and pencilled backface signature imprint from a clay block is shown in figure 1. Whilst such injuries have been observed they are still rare but the main effect has been to cause certification authorities to retain a backface signature test within armour type approvals.

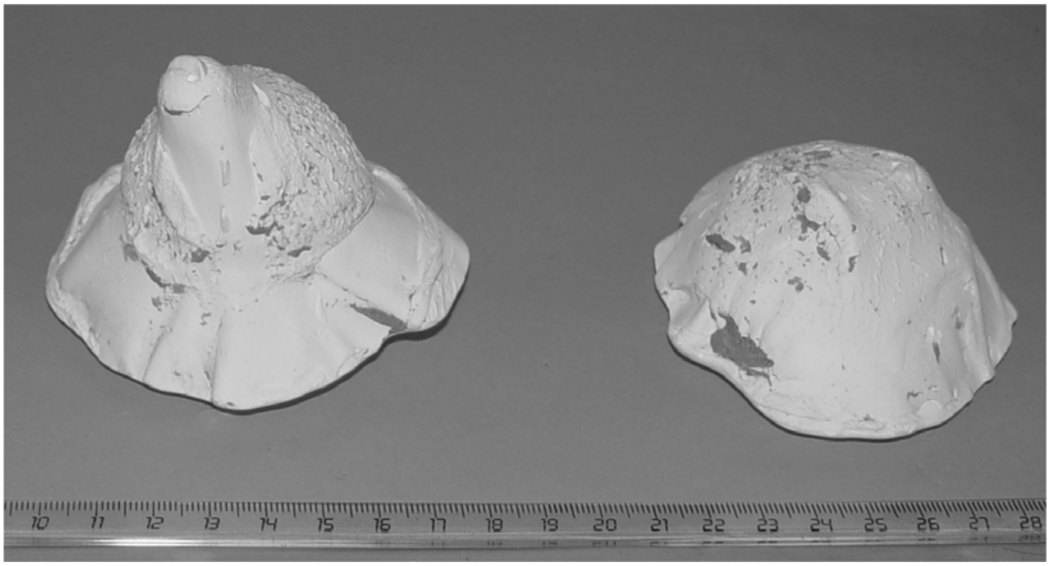

Figure 1. Plaster casts of backface deformation onto a clay backing behind a textile armour showing a pencilled impact (left) and a blunt impact (right).

3. ARMOUR AND THREAT CHARACTERISTICS

Given that the purpose of the armour is to resist penetration, the next step is to examine the mechanisms of penetration. In order to damage a target the aim will be to maximise kinetic energy delivered to and absorbed by the target. However, if the target is armoured then the projectile needs first to defeat this armour. Armour defeat requires that the energy is deposited in a form which causes the armour to be penetrated. This usually means that it must be concentrated over a sufficiently small area to achieve penetration; the degree of concentration of impact energy is referred to as kinetic energy density (KED). This is defined as the energy at impact divided by the presented area of the projectile. This is probably the best single measure of penetration capability. As the KED is a measure of penetrative capacity it follows that a higher KED threat will require more penetration resistant armour. Hence the KED will be a major factor in determining the type of armour required to defeat a given threat.

In addition to the KED, the velocity of the projectile is also important as the contact load is typically related to the square of the impact velocity. So a sharp or fast projectile will be very penetrative whilst a blunt or slow projectile will be less penetrative. The impact energy may not need to be absorbed by the armour but it is necessary to spread the impact load so that the wearer is not injured. Therefore the incident kinetic energy will also be a factor in armour defeat.

Table 1 summarises typical threats to body armour and the corresponding armour types which are used to defeat them. A typical threat to a policeman might be a handgun such as a .357” Magnum. This threat is included in most body armour test standards such as those issued by the US National Institute of Justice (Mukasey et al. 2008) and the UK Home Office (Croft & Longhurst 2007a). The .357” Magnum is regarded as a powerful handgun but it usually uses a soft-point ammunition that is designed to mushroom and dissipate its energy quickly on impact with a soft target such as a human body. The projectile has a relatively low KED in the un-deformed state but this is lowered further by the post impact deformation of the form shown in figure 2. Therefore any reasonably penetration resistant material should be capable of resisting penetration of this type of projectile. As the armour needs to be worn on the body it is useful if it is both thin and flexible. Flexibility has the additional advantage that it will allow the armour to deform rearwards providing additional time or distance to transfer the impact energy. It has been found that textile body armour based on multiple layers of high strength fabrics is capable of resisting penetration at the KED levels of the order of 20Jmm-^{2} which is typical of hand gun threats. The total kinetic energy is relatively low so textile armour does not require additional energy attenuation processes and is the most efficient solution.

Figure 2. A 0.357” Magnum soft point projectile before firing (left), and deformed after impact with a textile armour (right).

Table 1. The characteristics of the main threat groups and the types of armour which are used to provide protection.

Threat	Velocity (ms^{-1})	Kinetic Energy (J)	Presented area (mm^2)	KED (Jmm^{-2})	Armour Material
Handgun (.357"Magnum)	450	1032	65 (initial) 254 (final)	16 4	Fabric
1.1g (17grain) fragment	450	111	24	4.5	Fabric
Bowie Knife	8	42	0.25	160	Special Fabric
Assault rifle (AK47)	720	2050	24	45	Composite plate
HV rifle (SA80)	940	1805	75	75	Ceramic plate

In modern warfare the primary threat tends to be from shell fragments which typically cause 60-80% of battlefield injuries (Ryan et al. 1991). These fragments can be generated by a range of weapons such as artillery shells, mortars and grenades, but are also the main lethal mechanism from mines and improvised explosive devices. Therefore it has become customary to provide troops with combat body armour capable of protecting against typical fragments. It is difficult to devise a repeatable test using fragmenting munitions and so for specification purposes armour is tested by the impact of a gun launched projectile called a fragment simulating projectile (FSP) (Army Research Laboratory 2008) (Figure 3). Military body armour is typically required to provide protection against a 1.1g (17grain) FSP (Eriksen 2003). At $400ms^{-1}$ the 1.1g FSP meets the 80J necessary for incapacitation and so most armour is designed to protect against it at impact velocities in the range $400ms^{-1}$ to $800ms^{-1}$. The KED of small fragments is in the same range as handgun bullets, therefore the construction of combat body armour is similar to that of police armour and uses multiple layers of high strength fabrics.

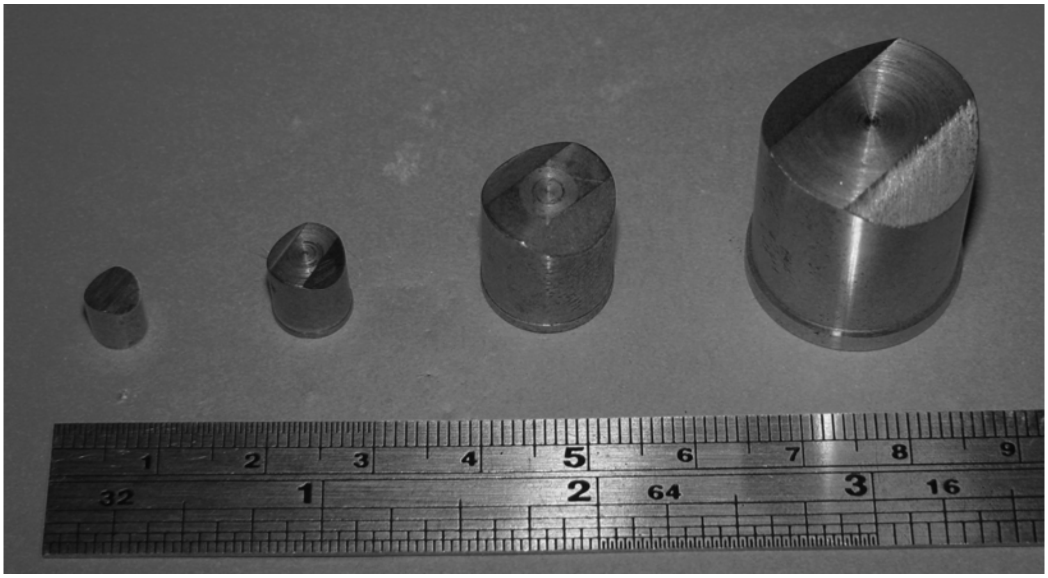

Figure 3. Fragment simulating projectiles (FSP) from left to right, 1.1g, .30”cal, 0.50”cal, and 20mm.

In regions where public gun ownership is low or within controlled areas such as prisons the knife becomes the prevalent threat. Knives and edged weapons are hand delivered so their velocity and hence kinetic energy is quite limited. However, the small contact area on the tip of a knife provides a very high KED which is easily capable of penetrating soft materials such as conventional high strength fabrics. Consequently knife resistant materials have been developed to provide the higher penetration resistance needed against high KED threats whilst preserving the thin and flexible properties of conventional textile body armour. Typical solutions have included modified fabrics, chain mail and articulated plates.

Finally, there are the highly penetrative threats afforded by modern assault rifles. Rifle bullets have a variety of characteristics ranging from relatively low KED types such as the Kalashnikov AK47, to more penetrative types such as 5.56mm projectiles of the M16 and SA80 assault rifles. In addition, it is possible to obtain hard cored armour piercing ammunition in most military calibres that provides an even more penetrative threat. This high penetrative capability and the high kinetic energy requires both a more resistant armour to achieve some energy transfer from the projectile and an ability to spread the contact loads to a much greater extent. The optimum armour solutions against high velocity rifle bullets range from polymer composites for the less penetrative projectiles to ceramic faced composite for higher velocity or harder types. These composite and ceramic faced composite armours are also used in suits worn by bomb disposal technicians to provide protection against very high velocity fragments experienced close to a bomb blast.

4. TEXTILE BALLISTIC BODY ARMOUR

Textile body armour has been used since the middle of the 20th Century but it can trace its roots back to the use of silk fabrics, leather and other multi layer systems of antiquity. The response of textile armour to ballistic impact is complex and not fully understood. Numerous studies of fabric systems have been published and the understanding has slowly developed based on single fibre tests, meso material models and recently to relatively complete numerical models of multi layer systems (Tabiei & Nilakantan 2008). Analytical and empirical models have been developed (Roylance 1977) (Cuniff 1999) which seek to indicate the key fibre and fabric properties required in armour. However our understanding is still somewhat incomplete with the more subtle effects, such as inter yarn and inter layer interactions remaining to be fully characterised and with models which are only validated across relatively narrow sets of conditions and materials.

Figure 4. The pyramidal deformation of an aramid fabric during ballistic impact of a 1.1g fragment simulating projectile.

The impact and capture of a projectile by multi layer textile armour can be summarised as follows. Upon impact with the first layer of the armour the material under the projectile is instantaneously accelerated to the projectile velocity. Above some critical velocity the contact load is such that the yarns are failed and only a small amount of energy is extracted from the projectile. But the projectile is progressively decelerated and the ensuing layers accelerated until yarn failure does not occur. Assuming the yarns do not immediately fail then a tensile wave propagates along the yarns away from the impact point and in doing so some energy is absorbed from the projectile. The yarns are also driven rearwards (i.e. in the direction of movement of the projectile) but this rearwards movement propagates as a transverse wave approximately one order of magnitude slower than the tensile wave. Both waves propagate along the yarns they have struck (called the primary yarns) and also branch into the crossing yarns (called secondary yarns). The action of the transverse wave in the primary and secondary yarns is to form a pyramid of material and it is the kinetic energy of the rearwards moving pyramid (Figure 4) which is the major dissipation mechanism during the early stage of impact. At later stages the elastic strain energy in the yarns starts to dominate the transfer process but it should be noted that as this is elastic strain the energy it is not being dissipated.

The impact process in effect requires two things from the fabric or yarns; firstly they should not break so they should be strong (or tough) and secondly the imposed load and the resulting stress waves need to move quickly from the impact point. This has led the combined performance factor U* (Cuniff 1999) which states that the performance of fabric is the product of the specific yarn toughness and longitudinal wave speed of the yarn

$$U^{*} = \frac{\sigma\varepsilon}{2\rho}\sqrt{\frac{E}{\rho}}$$

Where σ, ε, ρ and E are the ultimate tensile strength, strain to failure, density and longitudinal wave speed of the yarn.

A number of other factors emerge as contributory properties of the fabric layer or armour system. If the yarns are loosely woven then there is a greater tendency for projectiles to part the yarns and penetrate without fully loading them; a process known a windowing. This effect is suppressed if the yarns are relatively closely woven; often this is described by a cover factor - the ratio of the projected area of the individual yarns to the area covered by the yarns when woven into fabric.

These requirements result in a construction consisting of multiple layers of dry fabric. Multiple layers are required as it is necessary to decelerate the projectile within a reasonable distance and also because the impact velocity may be above the critical velocity of the first layers. It has been shown that thin armours are less efficient than thick armours but they are much better at stopping projectiles in short distances.

The majority of textile systems use the same fabric type throughout their thickness but there are examples of armour using varied types. For instance the requirement for high cover factors is only for the layers in contact with the projectile so it may be beneficial to have high cover factors fabrics towards the impact face and coarser weave fabric to the rear. A preference towards lower cover factor coarse fabrics is economic as cost tends to scale with thread count.

Although BABT is not a common problem there is a necessity to limit the deformation of the armour to a reasonable level. In this context test standards require that when tested on a clay based backing material the resulting depression or backface signature must not exceed some limiting depth such as 44mm (Mukasey et al. 2008) or 25mm (John Croft & Longhurst 2007a). The validity of these particular limits and the exact correlation of these backface signatures to BABT injury is unclear although it has received some attention (Wilhelm & Bir 2008). In any case, it is often necessary to modify the armour system construction in order to achieve a suitably low level of backface signature. Typical constructions use stiffened fabrics, padding or even steel ‘shock plates’ behind the basic fabric pack.

These more peripheral design features mark the major difference between police armour systems and military armour systems. Current systems are almost entirely empirically designed and this has tended to indicate a number of threat and market driven optimisations. A police system designed to stop low velocity but relatively heavy handgun projectiles will often need to limit backface signature to work within specification. There are characteristic of handgun bullets which seem to favour tightly woven fabrics, although the reasons are not clear. Military systems are often only required to stop the 1.1g FSP which has insufficient kinetic energy to cause any backface signature so there is no need for trauma attenuation layers.

In addition to these variations in the fibre properties, the ballistic properties are also influenced by factors within the fabric manufacture. Ballistic performance is usually improved by using a finer yarn, greater tightness of weave and optimising weave style. For example in one study an older design of armour used a 1500 denier Kevlar® 29 yarn giving a ballistic limit velocity of 370ms^{-1} against a military fragment threat. A more recent design of the same weight of armour against the same threat uses 600 denier Kevlar KM2® yarn has a ballistic limit velocity of 520 ms^{-1} (Ren 2002). It should be possible to further improve ballistic performance by using a unidirectional or non-crimped fabric as the crimp inherent in any woven fabric hinders load transmission along the fibre.

5. KNIFE ARMOUR

The threat from edged or pointed weapons is inherently variable because they are propelled manually, by a population with a wide variety of abilities and techniques. In addition the definition of edged weapons may cover a wide variety of knives, tools, swords and other implements which may have various degrees of sharpness and different types of cutting edges. Unlike ballistic armour it is difficult to specify a typical weapon which represents a worst case threat; it is only possible to determine the range of weapons and attacks which may be expected. Current and previous test procedures (Croft & Longhurst 2007b)(Petit & Croft 1999) (H P White 1988)(Parker 1993) have included a variety of knives and spikes as illustrated in figure 5.

Figure 5. Typical edged weapons a) Lock knife, b) ‘Survival’ knife, c) Kitchen knife, d) ‘Bowie’ knife, e) Craft knife, f) Screwdriver, g) HP White spike (H.P. White 1988), h) American ice pick, i) PSDB N^{o}1 test knife (Parker 1993), j) PSDB N^{o}5 test knife (Parker 1993) , k) HOSDB P1/B test blade (Croft & Longhurst 2007b), l) HOSDB Spike (Croft & Longhurst 2007b).

Bleetman (1996) analysed the injuries presented in hospital emergency admissions by ordinary members of the public and examined the likely requirement of stab resistant armour to prevent stabbing injuries. It was found that the injury mechanism of stabbing was primarily blood loss and associated complications so lacerations to the liver, spleen, lungs or outer parts of the gut can cause bleeding which is potentially life threatening. Other injuries might include punctures to the chest wall leading to lung collapse, whilst damage to the heart and associated major arteries may be almost immediately fatal. It should be noted that the significant mechanism is the profuse blood loss and its associated complications rather than direct organ failure. A later study (Connor et al. 1998) assessed the depth of penetration required in order to cause damage to vital organs. Whole body computer tomography scans were used to determine skin to organ distances for a group of 71 subjects. It was found that the minimum distance of vital organs from the skin surface was approximately 10mm whilst median distances were of the order of 20mm.

A number of studies have been made of the type and location of stab wounds and particularly of fatal wounds. A study of stab wounds according to impact site (Rouse 1994) found that out of a total of 69 single fatal wounds 50 were to the chest, 12 to the head and neck, and 7 to the abdomen and lower limbs. For multiple fatal wounds (81 cases), the wound causing the fatality was to the chest in 61 cases. In another study (Murray & Green 1987) it was found that of 27 single fatal wounds 18 were to the chest. It can be concluded from these studies that fatalities from stabbing are in the majority of cases due to chest injuries. Therefore protection of the chest will carry the highest priority if the aim is to prevent fatal stabbing attacks. Armour protection should extend over as much of the torso as possible and should also cover the upper legs and pelvis if protection is to be maximised

The penetrative power of knives is a product of the energy density achieved at the tip of the knife combined with the ability of the cutting edge to easily enlarge the perforation. Current test standards require knife resistance for impact energies in the range 25-43 Joules, although this is much lower than the impact energy of a bullet it is applied over a very small area. This leads to very high contact forces such that the materials of the armour is indented and forced radially and backward away from the knife (figure 6a). In essence the problem is that the reverse of that in textile ballistic armour as the knife has little kinetic energy but it is difficult to extract this energy into the armour. A relatively blunt knife might have a tip radius of 0.25mm and an average person might produce a stab of about 40 J yet this will still result in a KED greater than that of a high velocity rifle bullet.

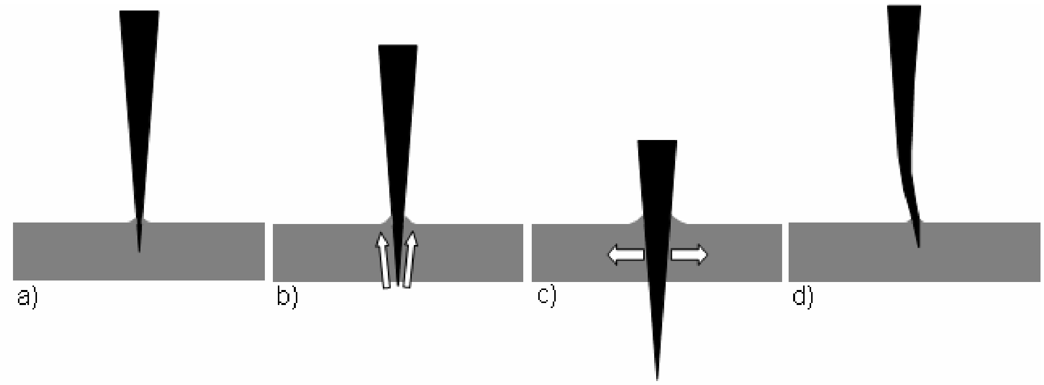

Figure 6. Various mechanisms of knife penetration, a) Initial penetration due to high contact loads, b) Frictional resistance to continued penetration, c) Resistance to hole enlargement, d) Buckling of the knife blade.

The simplest method of providing stab resistance is to use rigid plates of metal or composite. Such materials are sufficiently hard to defeat knives by resistance to indentation and to present a large resistance to further penetration should perforation occur (figure 6b-c). Metallic systems can offer good protection if they have sufficient hardness. Softer metals such as aluminium require greater thickness to achieve protection but are relatively light. Best results have been achieved with titanium and its alloys (Horsfall 2000) however these tend to be costly. Titanium has the advantage of a very high work hardening rate and high toughness making it extremely resistant to puncture or cutting.

Rigid armour may defeat a knife by simply resisting perforation or by causing the blade tip to buckle (Figure 6d). Thin sharp blades such as those found on domestic knives (Figure 5c) will have a tendency to break or buckle. Heavily constructed blades such as those used for outdoor ‘survival’ purposes (Figure 5b) will be much less likely to buckle but their large cross sections will require large perforations to be produced in the armour. The different behaviour of thin sharp blades versus large heavy blades lead to the adoption of both types in early armour test standards (Figure 5i-j)(Parker 1993).

The main disadvantages of rigid armour are in wearer comfort and coverage. In order to allow sufficient movement of the arms and waist it is necessary to either reduce the coverage area or provide some means of articulation within the plates. The most common solution is to use multiple plates, these may be loosely held in multiple layers or some form of hinges may be fitted to the edges of single plates. Plate edges provide weak points in the armour, multiple layers increase both weight and bulk whilst effective and durable hinging appears to be difficult to achieve in practice. Such systems have become less common in recent years as fabric and chain mail systems have been sufficiently developed to give equivalent protection with greater flexibility and lower weight.

Rigid armours have another important disadvantage; they cannot undergo significant bending or large scale deflection and must stop the threat within their own thickness.

This tends to mean that relatively hard or thick plates are needed to provide the required protection. This is in contrast to typical textile ballistic armour systems which deform rearwards into the wearer's body to allow efficient energy transfer over a distance much greater than their original thickness.

A better solution for knife protection would be fully flexible textile armour similar to that used for hand gun protection. This is possible if measures are taken to increase the cutting and perforation resistance of the weave. Most fibres have some resistance to cutting; aramid fibres such as Kevlar® and Twaron® probably being the best of the polymer types. However it is important that the knife is forced to cut these fibres rather than simply parting the weave. Measures must be taken to stabilise the weave and prevent the yarns or fibres being forced apart. This can be partially achieved by using much finer and tightly woven yarns. A low denier yarn is used and this is woven as tightly as possible with a correspondingly high cover factor. This approach is particularly successful against spikes (Figure 5f-h) and has seen significant applications in armour for prison guards who are typically exposed to improvised spike-like weapons. As the spike has no cutting edges it is possible to prevent perforation simply by resisting the opening of the weave. The advantage of these systems is that they retain the full flexibility of textile armour and may offer some level of ballistic protection at the same time.

Another method of improving fabric stability is to coat or laminate the fabric with a thin polymer layer so that the yarns are partially bonded together (Mayo et al. 2009). Although this solution reduces the fabric flexibility with consequent reductions in comfort and ballistic properties it may reduce the incidence of blunt trauma in ballistic and blunt attack. It is also possible to laminate an abrasive onto the fabric which enhances the frictional interaction with a knife.

Laminated textile armour is able to confer both knife and ballistic protection within a armour of reasonable flexibility and simple construction. These systems have become the dominant construction in the 21st Century. The change from rigid or semi rigid systems to flexible ones has been partially a result of improved test and specification processes. More recent standards for knife resistant armour have adopted changes which tend to favour compliant armour which deforms under impact conditions (Croft & Longhurst 2007b) . A test knife is propelled into the armour under the action of gravity with the knife mounted ahead of a 1.25kg drop missile on a compliant mounting. This replicates the relatively extended kinetic energy transfer that occurs in a real stabbing event (Horsfall 1999). The armour is mounted on a soft foam support which reproduces the compliance of a human chest and allows deformation of the armour. The result of this test method is that optimised armour will tend to be as flexible as possible to allow rearward deformation whilst at the same time having sufficient perforation resistance to prevent failure. The test standard allows up to 7mm perforation, information that was derived from earlier studies (Connor et al. 1998).

Chain mail can also be used as a flexible knife resistant armour. In this case the action of the chain links is to capture the blades tip after a small amount of perforation. It is therefore necessary to use either a very fine chain link diameter or to use a padding system. Typically the armour systems will consist of a layer of chain mail positioned on the front face of a conventional multi layer ballistic fabric pack. This construction has very good flexibility and provides both knife and ballistic protection at a comparable, although slightly greater weight than a laminated fabric solution. It is however typically more flexible than the laminated fabric and has found particular use in female armour which needs this greater flexibility to allow for breast shape.

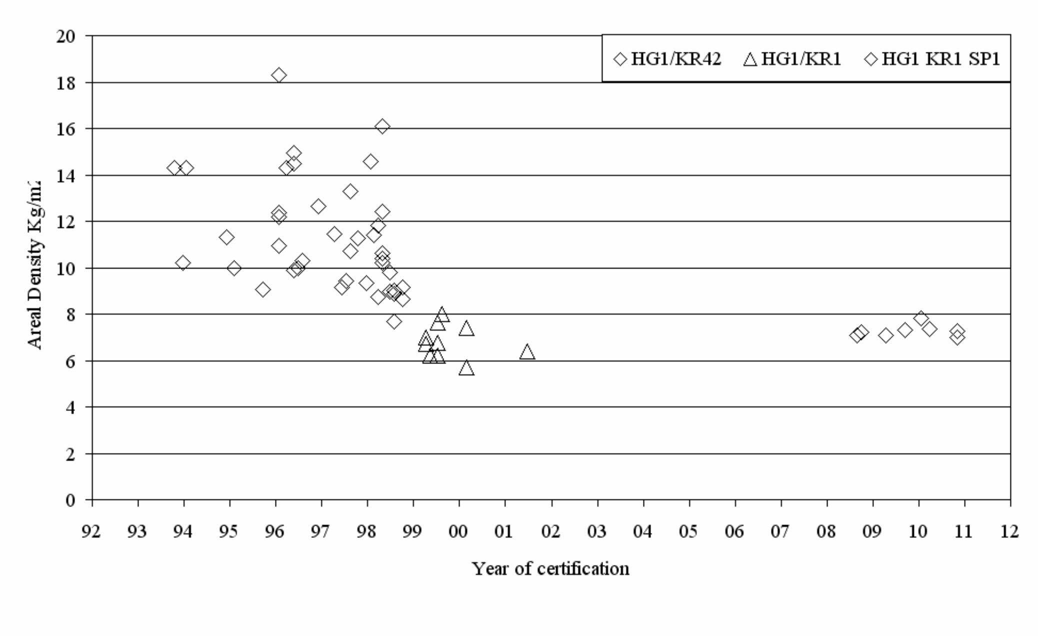

Figure 7. Areal density of UK Home Office approved knife and ballistic resistant armour systems. HG1/KR42 tested according to the 1993 standard(Parker 1993), HG1/KR1 tested according to the 1999 standard (Petit & Croft 1999), and KR1 HG1 SP1 is tested to the 2007 standard(Croft & Longhurst 2007b).

Developments in knife and ballistic armour technology have led to a decrease in armour mass over recent years. This has also been accompanied by an increase in the flexibility of the armour systems and improved design. In the UK, police body armour is generally required to provide knife and ballistic protection. Initially the combined armour systems were both heavy and uncomfortable to wear. A change to the compliant knife missile and test support has allowed development of better knife resistant systems. When combined with advances in armour technology and experience this has produced lighter systems and at the same time the armour has become more flexible. The UK Home Office has for the last 20 years tested and measured the performance of police body armour. Examination of the publicly available data shows that the areal density (weight per unit area) of approved systems has reduced by almost a factor of three over the period of 1993 to 2010 as shown in figure 7. The data in the figure 7 is for armour which is certificated against the UK Home office low handgun threat (HG1) and a knife threat (KR42 or KR1) according to the test standards in force at the time. In recent years the test standards have required armour of greater reliability and reproducibility which probably explains the lack of further weight reductions between 2002 and 2008.

5. HIGH VELOCITY BALLISTIC ARMOUR

For bullets having a KED of above 30Jmm^{-2} ballistic fabric systems become overly bulky. The contact loads tend to be sufficient to cause shear failure of the fibres and capture of the projectile occurs only after numerous layers have been perforated. For KED of 30-45Jmm^{-2} it is possible to provide protection by use of polymer matrix composites. In essence this is an extension of the tactic used in knife armour as the projectile is forced to break fibres and radially expand the perforation against significant constraint. It has been shown that at low KED flexibility is a key factor in projectile capture whilst at higher KED shear strength within the material becomes dominant (Walker 2001). In effect this marks a transition from a net like behaviour to a penetration and absorption behaviour. The 30-45Jmm^{-2} KED regime is of some practical importance as the slower velocity assault rifle projectiles such as those of the Kalashnikov AK47 fall within this range. Polyethylene fibre composites based on Spectra® or Dyneema® provide the most weight efficient systems in this range.

Most western assault rifles use higher power ammunition in 7.62mm and 5.56mm calibres which result in higher velocity impacts with KED of 50Jmm^{-2} or greater. In this regime it is necessary to promote disruption of the projectile in order to expand the contact area and reduce the KED. This is usually achieved with a hard ceramic disruptor layer, bonded to a tough backing or absorber. This disruptor-absorber structure provides an efficient mechanism to dissipate the energy of high velocity and hard cored projectiles.

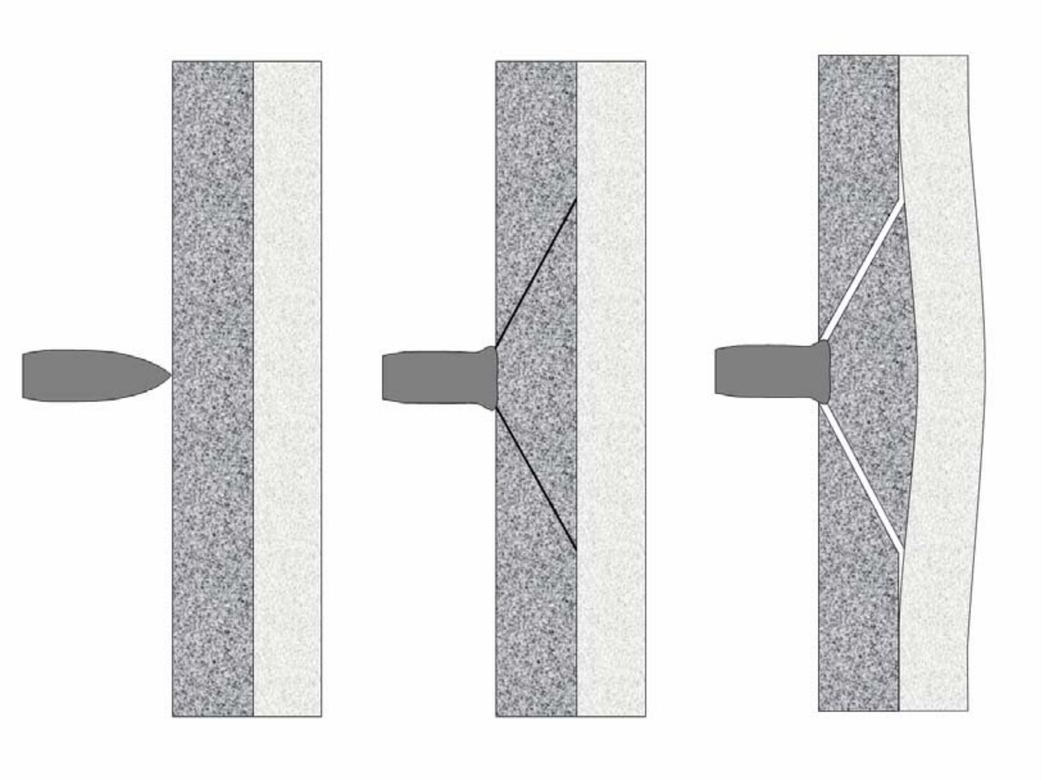

Figure 8. Stages in the defeat of a projectile by a ceramic faced armour system.

On impact with the ceramic face the projectile is either shattered or mushroomed. This process may result in some lowering of the incident KED as the contact patch is spread out. Under the contact paths the ceramic is in compression and initially resists break up, even when fracture does occur the resulting ceramic rubble will provide considerable resistance.   At the edge of the contact patch tensile stresses develop and lead to a ring crack which then grows into the ceramic forming a conoid with an included angle of approximately 130°. This material spreads the imposed load onto the backing resulting in a low KED on the rear face of the ceramic as the projectile pushes the conoid base into the backing (figure 8). Little energy is absorbed by the cracking or shattering of the ceramic and most of the impact energy is transferred to the backing material . It is possible to quite accurately predict the ballistic performance of a ceramic faced armour simply from a knowledge of the ceramic thickness and absorbing characteristics of the backing materials (Florence 1969).

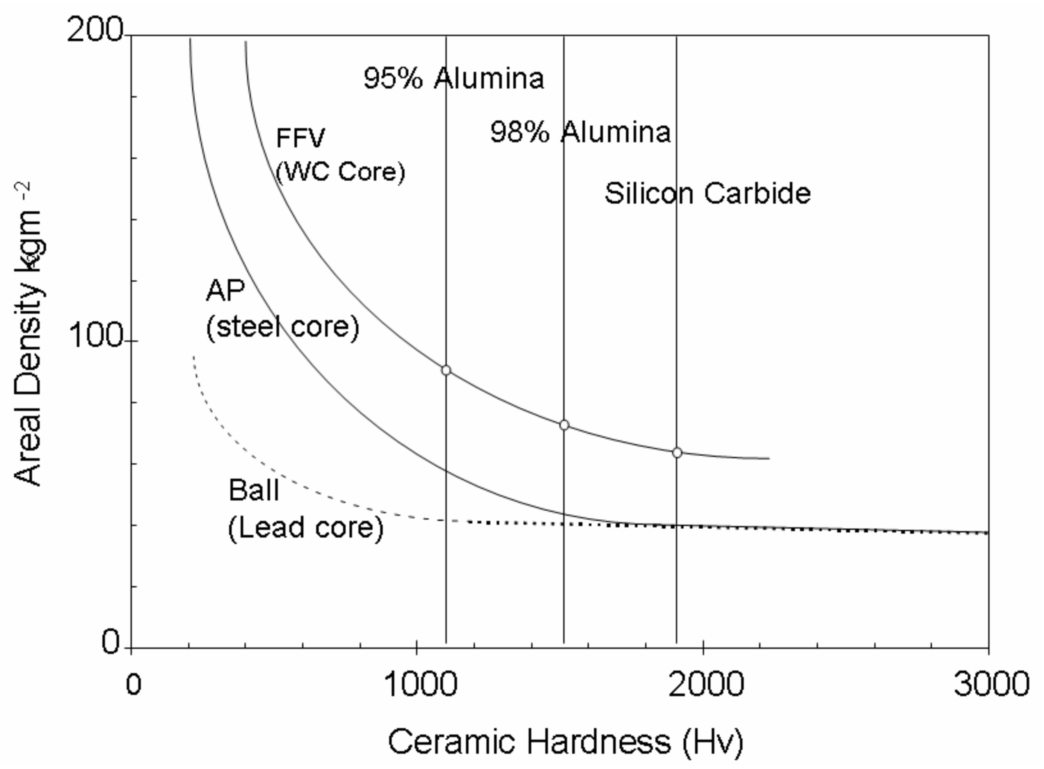

Figure 9. The effect of projectile type on the areal density and type of ceramic required to provide protection.

A number of studies have shown that ballistic performance of ceramic faced armour scales to some extent with hardness of the ceramic. The ceramic must have a hardness that is significantly greater than that of the projectile (Anderson et al. 1996) so that it can resist penetration. For soft cored projectiles (lead cored ‘ball’ ammunition) a relatively low grade ceramic such as a 95% pure alumina is appropriate. For hard steel cored armour piercing (AP) based projectiles, which are common in light armour piercing ammunition, there is some advantage to using a higher grade (98% pure) alumina. However tungsten carbide (WC) cored projectiles have a hardness level equal to or greater than most alumina compositions. Therefore where such hard-cored projectiles are a threat there is a need to choose ceramic materials such as silicon carbide as illustrated in figure 9.

The absorber materials are in most cases very tough polymer composites. These may consist of aramid fibres in a tough matrix such as heavily plasticised and toughened polymer resin or neoprene. Polyethylene fibre composites are also widely used although typically these consist of pressure consolidated laminates rather than using resin infiltration. Most systems have a covering of fibre composite or fabric to provide an impact resistant and to enhance the damage tolerance of the system. Optimisation studies (Hetherington 1992) have shown that the ceramic face should amount to approximately two thirds of the total mass of the system with the absorber making up the rest. Another purely empirical rule of thumb is that the ceramic layer should have a thickness approximately equal to the threat weapon calibre.

The ceramic faced armour is typically used in the form of a large plate which may be worn on the front and/or rear of the torso. Armour of this type is common in military service with a range of plate types and sizes being available. Some armour designs also incorporate ceramic faced plates on the sides of the torso and the shoulders although such designs become cumbersome and are limited to use in high risk and largely static applications. Textile body armour is typically used to back and mount the ceramic faced and serves as a last energy-absorbing layer. This backing also provides protection to the whole torso against lower level threats whilst the rigid panel typically only covers the centre of the torso.

6. CONCLUSIONS

The protection requirements of body armour can be reduced to two processes; a need to promote an interaction mechanism to extract kinetic energy from the projectile, and a mechanism to disperse this energy without transferring excessive loads or deformation into the wearer.

Handgun bullets deform easily and so provide a simple interaction mechanism with fabric armour. However the energy of these projectiles is sufficient that care is needed to prevent excessive intrusion of the armour into the wearer’s body. High strength fabrics in suitably constructed systems provide an efficient solution.

Edged weapons such as knives represent a very penetrative threat which requires special fabrics or metals in order to generate an interaction with the armour. However the total energy of the impact is sufficiently low that no special measures are required to dissipate or spread the induced loads. Typical solutions include specialised fabrics, chain mail and articulated metal plates.

For protection against high velocity bullets there is a twin problem of providing penetration resistance and of dissipating large amounts of energy and associated shock loads. A full solution requires a combination of composite plates often with a ceramic facing and ballistic fabric backing layers to provide support and to give good coverage.

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