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An Overview of Ceramic Armor Applications

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ANNOTATION

The increasing capability of modern anti-armor threats and the need to field lower weight combat vehicles, capable of engaging an opponent with little preparation, have intensified the need for highly effective passive armor systems. Ceramic armor technology offers significant advantages for meeting future protection requirement. The investigation and application of ceramics against small arms threats has a long history, dating back to the early 1960s and the ballistic performance of ceramic armors for personnel protection is very high; the principles governing these defeat mechanisms and the design parameters against such threats are now generally understood. However, achieving similar ceramic performance versus larger caliber, kinetic energy penetrator threats have long presented a difficult challenge. This paper presents an overview and discussion of the ballistic requirements, ceramic design factors and a chronology of significant U.S. developments and applications of ceramics for armor.

1. INTRODUCTION

The application of ceramics for armor continues to be primarily used in lightweight armor systems for protection against small arms and machine gun threats. The design of these systems is typically based upon the mechanical properties of the ceramic to fracture the penetrator and the ability of a rear compliant layer to catch the projectile debris and the damaged ceramic material. For defeat of these low-velocity, short projectiles, the fracture mechanism occurs very early in the process with the majority of the interaction time dedicated to energy conversion of the kinetic energy of the debris into deformation and delamination of compliant backing. For medium caliber and heavy armor applications, where the dominant threat is modern, high velocity, heavy metal eroding projectiles, the defeat mechanisms are much more complicated and of longer time duration. For the past three decades, a wide variety of research programs, both domestic and foreign, have focused on developing improved ceramic armor systems for the defeat of these threats. This paper presents an overview and discussion of the ballistic requirements, ceramic design factors and a chronology of significant developments and applications of ceramics for armor, with emphasis on research conducted on ceramic armors at the U.S. Army Research Laboratory (ARL).

2. TERMINAL BALLISTIC EFFECTS

A review of the difference in terminal ballistic effects observed during the interaction of different classes and caliber's of kinetic energy (KE) projectiles is important to understand the required defeat mechanisms and armor designs. The delineation between the threat projectiles is primary related to the caliber, velocity and energy available, but is not exact and some projectiles cross over into the two categories discussed below. While the penetrator/target interactions for these two categories involve similar processes, defeat of the higher performance, long rod threats require different emphasis in the armor design parameters to be successful and the progress has been much slower.

2.1 Small Arms/Heavy Machine Gun Defeat

Historically, ceramic composite armor systems were designed to defeat armor-piercing (AP), kinetic energy projectiles, mainly in the small arms and heavy machine gun category. These AP projectiles are purely inertial rounds, most commonly made of hard steel (HRc 60-64), of moderate density (7.85 g/cm^3) with a few select rounds employing even harder tungsten carbide (WC) cores at higher densities (13.5-15.0 g/cm^3). The hard core is generally encased in a thin jacket of a more ductile metal for interior ballistic or aerodynamic considerations, but penetration performance of the bullet is controlled by the core properties. Such projectiles typically have a length to diameter (L/D) ratio in the range of 3:1 to 5:1 with moderate muzzle velocities of less than 1 km/s. The generally accepted high-end caliber is 14.5-mm, typified by the Soviet KPV family of heavy machine guns. Some saboted, light armor-piercing (SLAP) rounds have velocities up to 1.3 km/s but with reduced core weight. Overall, these projectiles tend to produce a total KE on the order of 10^3 - 10^4 J.

Early Research [1–4] discovered that the perforation of ceramic armor systems occurred in three general stages: **1. shattering; 2. erosion;** and **3. catching**. During the shattering phase, the penetrator fractures and breaks on the surface of the ceramic plate; the high compressive strength of the ceramic overmatches the loading produced by the penetrator impact, and the penetrator material flows and shatters. This initial stage is followed by a period of damage accumulation in the ceramic material initiated by tensile wave reflections, and bending of the ceramic tile and backing plate. During the second stage of ceramic armor penetration, the ceramic material is cracking, but the ceramic material can still contribute to defeat of the penetrator core through erosion mechanisms. In the final catching phase, the ceramic has lost considerable strength, but ceramic and backing combine to reduce the velocity through momentum transfer mechanisms.

The defeat mechanism for hard-core AP projectiles is primarily stages 1 and 3 with projectile fracture upon impact against an armor plate having sufficient hardness and/or high obliquity. The shattering and subsequent dispersion of the fragments result in a dissipation of the kinetic energy of the core over a larger area than if intact, thereby achieving defeat of the round with a reduced amount of armor plate. Monolithic ceramic plates were best suited to produce the shattering phenomena due to their high hardness and low densities. However, ceramic armor

requires a backup component to support the ceramic and delay failure during the initial impact/shattering interaction; the backup component then serves to absorb the residual projectile fragments and comminuted ceramic particles (Phase 3). The state of the art in protection against small arms threats is typified in lightweight, two-component ceramic faced composite armors designed for use in breast plates for personnel body armor, armored helicopter seats and appliques to metal or composite based vehicle structures.

2.2 Heavy Metal Long Rod KE Projectile Defeat

The mechanism for defeat of long rod penetrators (LRP) is more complex than for the conventional AP projectiles described above. These penetrators are commonly made of high strength, high density materials, such as tungsten sintered alloy or depleted uranium, having densities near 18 g/cm^3 with moderate hardness, good toughness and ductility; hence, the projectiles are not susceptible to shattering as hard core, relatively brittle, AP projectiles. This category includes APDS and armor-piercing, discarding-sabot, fin stabilized (APDSFS) projectiles, in calibers from 20-mm up to >140-mm. These LRPs are designed with a high L/D ratio (currently fielded examples exceed 30:1) and the high density core material coupled with relatively high muzzle velocity (1.3 - >1.6 km/s), yields KE in excess of 10^6 J, creating a high energy density per unit area of target impacted than with a corresponding hard core AP round. These factors, when combined with the greater projectile length and reduced propensity for fracture, makes the LRP a much more effective penetrator. Even if the frontal portion of the LRP can be effectively damaged, a substantial portion of the rod remains to continue the armor penetration process. Thus, the conditions that allow a simple ceramic composite to function effectively for small arms defeat do not apply when the armor is impacted by a LRP. The primary defeat mechanism is erosion (Phase 2) and the effectiveness is relatively low for simple ceramic armor systems.

3. MAJOR DEVELOPMENTS IN CERAMIC ARMOR TECHNOLOGY

Attempts to increase performance of ceramic tiles continued during the 1980's to present, as penetrator threats evolved. Researchers realized that increased efficiency of ceramics might be possible by lengthening the duration of the shattering stage of the penetration process, and/or by increasing the efficiency of the erosion process of the comminuted ceramic material. These researchers found that modest lateral confinement allowed constraint of the broken ceramic pieces, thereby enhancing the erosion phase of the ceramic penetration process. This confinement could be obtained by casting, as seen in the then very efficient armor developed in 1984-86 by ABEX-NORTON where silicon carbide tiles were inserted into very accurately cast aluminum matrices [5] (Figure 1). Additional examples include test geometry's proposed by Woolsey



Figure 1. Abex-Norton Ceramic/ Metal Composite Armor

and others [6,7] to provide a stiff and substantial confinement of the ceramic tiles in depth of penetration (DOP) configurations.

The most significant observations during this period, however, were in 1987 by Hauver et al [8] who examined test geometry's that delayed the generation of damage in the ceramic tile, thereby increasing the duration of the shattering phase of the penetrator defeat process. As penetrator threats increased in length and L/D ratio, Hauver realized that the shattering stage duration was critical to the overall efficiency of the ceramic defeat process; he demonstrated ceramic tile confinement geometry's that substantially increased the shattering/erosion phase of the penetrator defeat process to completely erode the penetrator (Dwell). These experiments employed compressive confinement of the ceramic tile (heat shrink of the metal surround), in combination with techniques to delay tensile wave and bending damage to the ceramic. The ceramic performance was enhanced through control of system geometry to minimize damage and increase the shattering stage of penetrator defeat. However, the overall mass and space efficiencies of these laboratory packages were low, due to the considerable confinement materials employed in the geometry.

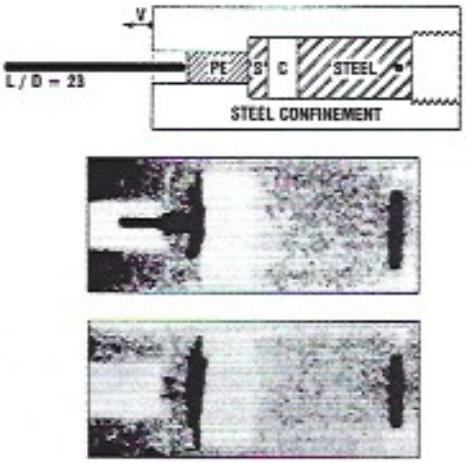
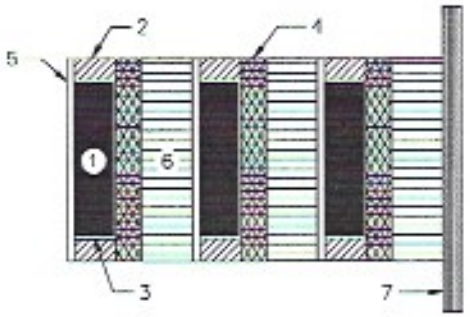


Figure 2. Hauver's Observation of Ceramic Dwell in Laboratory Confinement Geometry

In 1994, research lead to the demonstration of a set of medium caliber and full-scale armor targets that incorporated existing ceramic defeat knowledge into an armor technology known as tandem ceramic armor (TCA) [9]. TCA determines the optimum performance of a specific cross-sectional ceramic armor design and then repeats the designs in multiple, shock-isolated sections; the performance is thus additive (Figure 3). Laboratory targets, utilizing conventional laminated ceramic-metal technology, demonstrated system designs that produced the state of the art for KE performance. A limiting factor, however, was the space requirements that grew as the penetrator performance increased.



TANDEM ARMOR SYSTEM
1. CERAMIC TILE
2. CONFINEMENT FRAME
3. POLYMERIC ADHESIVE
4. SUPPORTING PLATE (METAL/COMPOSITE)
5. THIN GRP SECTION (OPTIONAL)
6. HONEYCOMB/ISOLATION MATERIAL
7. VEHICLE HULL

Figure 3. Tandem Ceramic Armor Concept

The latest efforts to generate increased efficiency in ceramic armors are to enhance both the erosion and "dwell" mechanisms of ceramic armor for penetrator defeat. The development of hot-isostatic-press (HIP) processing of ceramics with metal surrounds (Figure 4) has demonstrated dwell on the ceramic front surface of laboratory scale threats at efficient armor system areal densities [10]. This HIP processing forms a macro-composite through the generation of residual compressive stresses (mismatch of thermal expansion coefficients of the ceramic tiles and metal confining plates) in the ceramic tile during cool down of the HIP assembly from the pressing temperature. The macro-composite is then able to withstand the large ballistic bending loads during round impact, so that the ceramic tile resists fracture and retains a high compressive strength. The macro-composite formed by HIP processing also keeps the broken ceramic pieces confined during the second erosive phase of the ceramic armor defeat process, should it occur, thus maintaining a high erosive efficiency.

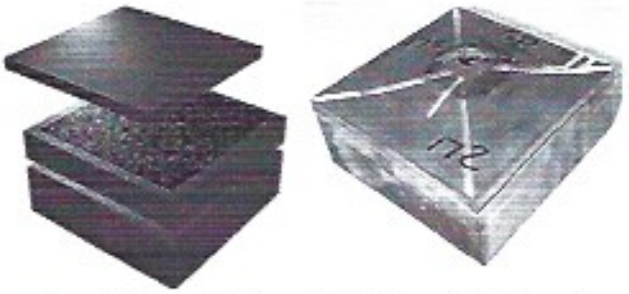


Figure 4. Hot-Isostatic Pressed Metal Encapsulated Ceramic

4. CERAMIC ARMOR DESIGN REQUIREMENTS

As with all armor systems, many design factors and production decisions influence the effectiveness of ceramic armors. These processes have to be understood and controlled to maintain performance.

4.1 CERAMIC TYPE

The technical ceramics available for armor are numerous, but generally are divided into the lower cost sintered and the higher cost hot-pressed ceramics. The higher cost ceramics are justified when the lowest areal weight system is the main requirement with the prime ceramics being boron carbide for body armor and airborne platforms and silicon carbide for ground vehicles. The high density tungsten carbide ceramic has specific applications where space is a limiting factor [11]. The lower cost sintered 99.5% aluminum

Table 1. Current Ceramic Armor Producers

Ceramic Type	Producer/Type
Sintered	Coors CAP3 99.5% Alumina Morgan Matroc (UK) Alumina ETEC Alumina Ceradyne Sintered SiC Pure Carbon SiC
Reaction-Bonded	M-Cubed (Simula) SiC MC^2 (Australia) SiC, B_4C
Metal Matrix Composite	Lanxide Dimox AS109 Lanxide Dimox-HT
Hot Pressed	Cercom B_4C, TiB_2, WC, SiC Ceradyne B_4C, TiB_2, SiC Saint-Gobain B_4C

oxide or silicon carbide or the reaction-bonded ceramics can be used were weight is not the driving requirement. However, for many armor applications, ultra-high hard steels, titanium or laminates of these materials with aluminum/composite backings are very competitive in performance with significant engineering advantages. Table 1 lists some of the primary producers of ceramics used today in armor applications.

4.2 Bonding/Impedance Effects

The use of hard face ceramic materials, bonded unto metal and composite backings, is typified in the classic work by Wilkens et al [12,13,14] on understanding the fundamental penetration mechanics that occur during the interaction of a hardcore steel projectile with a hard face aluminum oxide ceramic on aluminum. The primary applications involve bonding the ceramic to the metal or composite backing with low-density, low-impedance, and low shear strength adhesives. The unfavorable impedance effects and induced tensile failure across these boundaries and at the lateral boundaries of the ceramic are well documented by Hauver [15,16,17] for eroding long rod penetrators.

A less understood, but equally important effect from the use of a low-shear strength adhesive has been documented by a number of researchers. In 1993, Furlong et al [18] presented an exact solution for the transmission of spherical waves across planar surfaces; the coefficients of reflection and refraction were shown to depend not only on the acoustic impedance's of the media, but also on the boundary conditions at the interface, the wave face curvature, and the source frequency. Three types of boundaries can exist: 1) *free*, as with a free standing ceramic plate; 2) *no shear-coupling*, as with two unbonded or lightly bonded plates or 3) *shear-coupling*, where good adhesion or coupling exists, allowing the transmission of transverse motion and stress. The latter shear-coupled or no slip condition provides the best interface for a ceramic/metal armor design. Similar investigations were conducted by Almc [19]. Leighton et al [20] discussed the increased ballistic performance of laminated ceramic-titanium composites that resulted from increased interlayer bond strength (strong, shear-coupled metallurgical bonds). These effects are inherent in functionally gradient materials (FGM) composites as observed by Gooch et al [21] where metal layers transition into the ceramic layers without interfaces.

4.3 Adhesive Thickness and Uniformity

In simple bonded ceramic-metal laminates, an important factor to eliminate variability in ballistic performance is to maintain a uniform adhesive bonding layer at the minimum thickness. Burkins [22] modified the standard DOP test configuration by examining the ballistic results of a set of Taguchi experiments where the rear ceramic/metal bond thickness and lateral side confinement bond thickness were varied. The least variance occurred with a minimum bond thickness for the side and rear. For DOP tests, the maximum bond thickness allowed for the rear and sides is 0.127-mm (0.005 in). The uniformity of the bond thickness is maintained by placing spacers in the adhesive.

4.4 Confinement and Stiffness

The design of efficient ceramic systems begins by considering the mechanisms by which a ceramic tile fails during loading and designing the armor system to reduce the stresses contributing to early failure of the ceramic tile. Consideration of the ballistic event with emphasis on penetrator interface defeat on the ceramic front surface (Figure 5) lead Horwath [23] to determine two primary areas of concern: (1) the compressional loading of the ceramic directly under the penetrator rod, and (2) the maximum flexure of the ceramic plate and tensile stress/strain at the ceramic plate rear surface. These two factors are heavily influenced by the side and rear confinement thickness and materials.

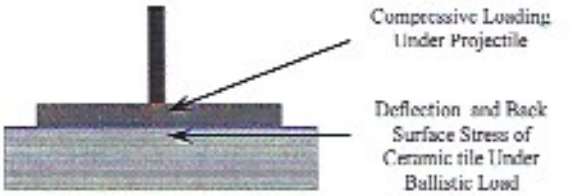


Figure 5.Primary Areas of Ceramic Tile

4.5 Multi-hit Requirements, Edge and Joint Impacts

As with all armor systems, the requirement to provide full protection against multiple impacts is still valid for ceramic armor designs. This requirement significantly impacts the design and tile size of ceramic designs. Table 2 lists the U.S. Army minimum impact spacing requirements for metals, metal laminates and ceramic laminates.

The requirement to impact edges or joints and maintain the same ballistic performance as center tile impacts is a major design requirement for most ceramic armor systems. Generally, ceramic design is driven by the edge or joint protection with the center providing greater protection. In some ceramic designs, the edges of the ceramic tiles are raised to increase the thickness to equalize the protection across the ceramic tile face. These factors result in increased areal weight for the design.

Table 2. Multi-hit Impact Requirements for Vehicular Armor

WEAPON CALIBER	METALS AND METAL LAMINATES* (mm)	CERAMIC LAMINATES* (mm)
7.62-mm	27	54
12.7-mm	45	90
14.5-mm	51	102
20-mm	70	140
23- to 25-mm	75	145
30- to 50-mm	76 (105)**	152

* Minimum spacing between impacts measured from center to center of impacts in vertical plane

** Full bore AP bullets only

5. APPLICATIONS OF CERAMIC ARMOR FOR COMBAT VEHICLES

The application of ceramics as the main protection technology has made major advances in the last decade and represents the accepted technology, in use today, for small arms and heavy machine gun protection, primarily as a ceramic laminate applique over metal structural base armors and a few, newer composite based systems. A few systems were designed against 30-mm APDS, but few armored systems have been designed against larger threats. The following paragraphs describe some of the military armor applications in use or development today. These are representative, but not inclusive, of the myriad examples of ceramic armors under development worldwide. The information was provided by the fabricators and producers of the ceramics and products.

5.1 Armorworks

Armorworks Incorporated of Tempe, AZ fabricates a wide range of ceramic composite products. Shown in Figure 6 is armored kit for an AH-60H helicopter floor. This armor system is an aluminum oxide based armor system that provides 7.62-mm APM2 protection at muzzle velocity. The armor kit consists of five panels, two of which are removable in flight (cargo hook access) and are nested in aft panel. The armor kit mounts on top of the floor panels using exiting fastener points on the floor with coverage of about 5.1-m^2 (55-ft^2). The armor panels passed MIL-STD-810E environmental testing including high and low temperature, solar radiation, sand and dust, salt fog, high pressure wash, humidity, fungus, vibration-resonance and vibration-endurance tests. The tile and backing are bonded; the gross panel shape is then fabricated by cutting and grinding and diamond saws and cores drills the holes to the final panel configuration.

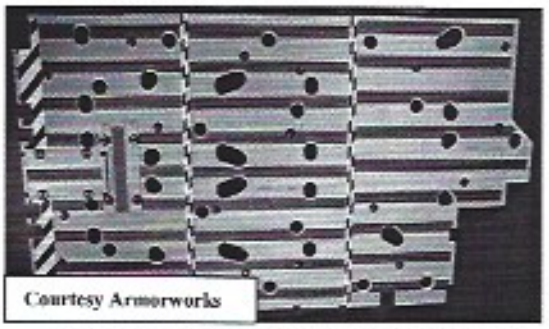


Figure 6. Armorworks AH-60H Floor Armor

5.2 Ceradyne Incorporated

Ceradyne Incorporated of Costa Mesa, CA develops and produces a wide range of advanced ceramics for many applications including ballistic grades such as hot-pressed boron carbide, silicon carbide and titanium diboride, pressureless sintered silicon carbide and reaction-bonded and sintered silicon nitride. Ceradyne has a long history of armor



Figure 7. Ceradyne Body Armor and Helicopter Seat

development beginning in the 1960's with the first applications of boron carbide for combat helicopter protection. Today, Ceradyne designs, develops and manufactures ceramic armor such as the ceramic breast plates and Cobra helicopter bucket seat of Figure 7.

5.3 Cercom Incorporated

Cercom Incorporated of Vista, CA has been a prime producer of a wide range of commercial and ballistic grades of ceramics since 1985. Using their pressure-assisted densification (PAD) process, Cercom has hot-pressed large quantities of aluminum nitride, boron carbide, silicon carbide, silicon nitride, titanium diboride and tungsten carbide ballistic ceramics for the U.S. Army. Figure 8 shows Cercom ceramic tiles on the European Tiger helicopter seat and two different types of Cercom hot-pressed boron carbide body armor inserts, a single-piece, compound curvature plate that is used in the U.S. Army Small Arms Protective Insert (SAPI) vest and two examples of multiple tiles fabricated into single protective inserts.



Figure 8. Cercom Ceramic Tiles for (L) Tiger Helicopter and (R) body armor inserts

5.4 German Ingenieurbüro Deisenroth

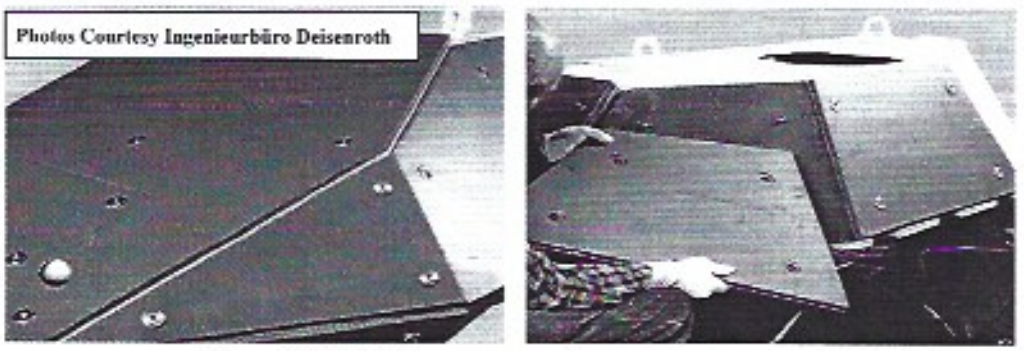
The German Company Ingenieurbüro Deisenroth (IBD) of Lohmar, Germany has established itself as a world leader in the variety and quantity of vehicles incorporating the MEXAS™ ceramic/metal/composite design; MEXAS™ stands for Modular, EXpandable Armor Systems and is composed of layered appliques that can be added to a basic vehicle structure to give the desired protection. While not conceptionally different from other appliques, the early use and continued application of this design is noteworthy and at least 39 different vehicles in ten countries utilize MEXAS™, including Austria, Switzerland, Germany, Canada, U.S., France, Italy, Finland, Sweden and Norway. Figure 9 provides a collage of the different vehicle types utilizing the MEXAS™ system, from engineer vehicles, tactical trucks, and numerous wheeled and tracked combat vehicles.



Photos Courtesy NDIIQ Canada and Ingenieurbüro Deisenroth

Figure 9. Examples of tactical and combat vehicles that mount IBD MEXAS™ armor

The design of the MEXAS™ system is shown in Figure 10 where a second layer of protection is being placed over the first. The vehicle structure provides the base protection and this system could be configured against three different missions or selective uparmoring of the vehicle. The panels are mounted by threaded attachment studs that accept special recessed fasteners.



Photos Courtesy Ingenieurbüro Deisenroth

Figure 10. Multiple layer concept of IBD MEXAS™ armor

5.5 Detroit Diesel General Motors of Canada

The Canadian National Defense Forces have been very active in providing increased protection for a wide range of tactical and support Canadian equipment. This requirement is driven by the deployment of their forces in a number of peace-keeping operations and the threat of increased small arms threats. Shown in Figure 11 is the Canadian LAV III Armored Personnel Carrier (APC) that has protection against small arms AP threats. The ceramic MEXAS™ composite armor is fabricated by the Canadian company DEW Engineering and Development Limited of Miramichi, New Brunswick, Canada under license to IBD. The characteristic mounting hardware of IBD armor is readily visible in the LAV III glacis area. DEW has supplied over 750 kits to the Canadian Defense Forces.