Invited Paper

Transparent ceramics for armor and EM window applications

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ABSTRACT

Recently, the U.S. Army Research Laboratory (ARL) has focused increased attention on the development of transparent armor material systems for a variety of applications. Future combat and non-combat environments will require lightweight, threat adjustable, multifunctional, and affordable armor. Current glass/polycarbonate technologies are not expected to meet the increased requirements. Results over the past few years indicate that the use of transparent crystalline ceramics greatly improve the performance of a system. These results coupled with recent processing and manufacturing advances have revitalized the interest in using transparent ceramics for armor systems. The materials currently under investigation at ARL are magnesium aluminate spinel ($MgAl_2O_4$), aluminum oxynitride spinel (AlON), single crystal sapphire (Al_2O_3), glasses, and glass-ceramics. The polymers under investigation are polycarbonate (PC) and polyurethane (PU). An overview of current ARL efforts in these areas, including the motivation for using transparent ceramics, the requirements, the potential applications, and the ongoing processing research will be reviewed.

Keywords: transparent, ceramic, armor, aluminum oxynitride, spinel, sapphire, polycarbonate, polyurethane

1. INTRODUCTION

1.0 Background

Transparent armor is a system constructed of different materials that are designed to defeat a particular threat or range of threats. The threats targeted are dependent on the envisioned combat or non-combat scenarios. There are also threat requirements for "operations other than war" where ballistic protection is required. Though a system is designed for a particular threat, there are general requirements common to most transparent armor systems. The paramount requirement for a transparent armor system is the defeat of a designated threat. The system must also provide a multi-hit capability with minimized distortion of surrounding areas of the first hit. For future land and air platforms, weight is a critical parameter that must be minimized. Space efficiency can also be quite important for certain applications. Other requirements for transparent armor windows are that they are night vision compatible, and they are affordable based on cost-performance models.

A simple solution that increases the ballistic performance of a window is increasing the thickness of the window. The material and design costs are thus, increased incrementally. For many applications, very thick armor systems are not practical solutions, even if they defeat the threat. Thick windows may be impractical for a few reasons. One is due to the increased weight associated with thicker materials. Another reason is the space limitations in many vehicles. Finally, thick sections of transparent armor have greater optical distortion than thinner sections, reducing the transparency. Therefore, new materials that are thinner, lightweight, and offer better ballistic performance are sought. Affordability is a critical metric for evaluating all armor systems and can be the limiting factor for given applications. There are many methods to measure the ballistic performance of a system. Several experimental techniques have been developed to aid in comparative studies of armor systems. One of these tests, a V_{50} test[1], was used to measure ballistic performance for the systems mentioned in this paper.

Figure 1 is a drawing of a general transparent armor configuration. As can be seen, the system is comprised of many layers, separated by polymer interlayers. The casing and support framing have been deleted to provide a better view. The front face (leftmost ply) is usually a hard face material that is designed to break up or deform the projectile upon impact. The sequential plys are added to provide additional resistance to penetration. These materials can be the same or different as the front ply material. An interlayer to join the two plates separates the plys and provides a transition between two materials that may have thermal expansion mismatches. The final plate is usually a polymer, polycarbonate (PC) or polyurethane(PU))

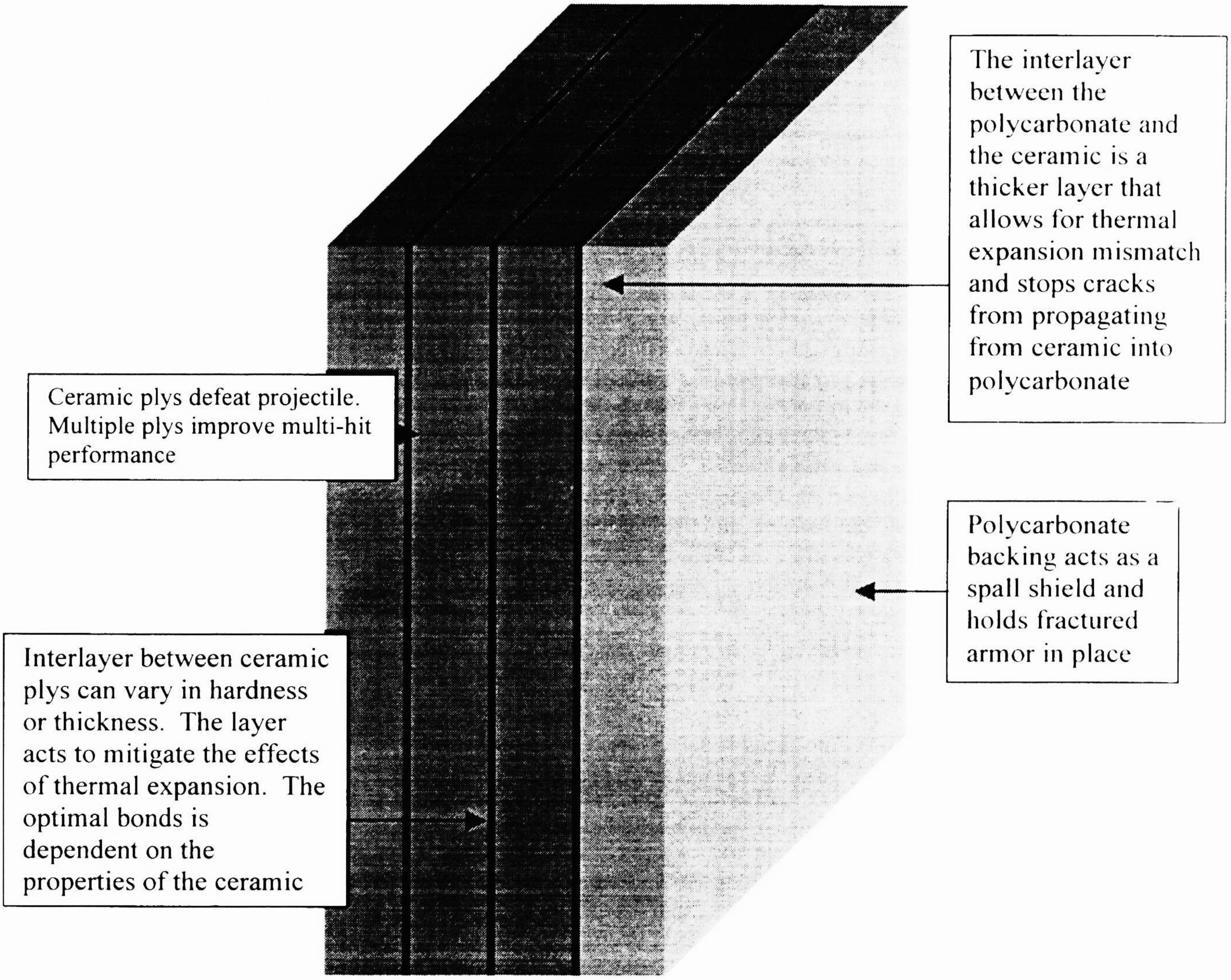

Figure 1

Schematic of a transparent armor system

with a thicker interlayer. The purpose of this interlayer is to mitigate the stresses from thermal expansion mismatches, as well as to stop crack propagation from ceramic to polymer.

The armor system can be engineered to provide different levels of protection. In addition to defeating the threat with multi-hit capability, the mass and space efficiency should be optimized to a given application. The variables that can be changed are plate material, thickness of plys, interlayer hardness, interlayer thickness, number of plys and the order of constituent materials.

2.0 MATERIALS USED FOR TRANSPARENT ARMOR:

2.1 Polymeric Materials:

The most common plastic used for transparent armor applications is polycarbonate. Polycarbonate offers excellent ballistic protection against small fragments. Polycarbonate is an inexpensive material that is easily formed or molded. Polycarbonate is used in applications such as the sun, wind, and dust (SWD) goggles, spectacles, visors, face shields and laser protection goggles. Polycarbonate is also used as a backing material for advanced threats. Polycarbonate is more effective in the thin dimensions required for individual protection than in the thicker sections required for vehicle protection. Though the material is adequate for many applications, the search for lighter weight materials has led to investigations into other polymeric materials such as transparent nylons, polyurethane, and acrylics.[2,3] The limiting factor for use of other transparent polymeric materials is their durability and their optical properties. Improvement in these properties would warrant an investigation into the ballistic properties of the material.

There have been efforts to improve the properties of polyurethane. Simula Technologies Inc.[+] has recently introduced a new family of polyurethane with improved optical properties. These materials are marketed and sold by Simula Polymer Systems Inc. Sim 2003 and Sim 1802 are both thermoset plastics that are produced by casting or liquid injection molding. Sim 1802 is harder and more brittle than Sim 2003. Due to their physical properties, Sim 2003 is a viable candidate to replace polycarbonate as a riot visor or as a backing material. Sim 1802 is a better candidate for front or hard-face material. These improvements in polyurethane have led to an investigation into these materials for face-shield applications (Section 3.1)

2.2 Glasses and glass-ceramics:

There are several glasses that are utilized in transparent armor. Normal plate glass (soda-lime-silica) is the most common glass used due to its low cost, but greater requirements for optical properties and ballistic performance generates the need for new materials. There are many different glasses including borosilicate glasses and fused silica that can be used. Glasses can be strengthened using chemical or thermal treatments. Controlled crystallization of certain glass systems can also produce transparent glass-ceramics. TransArm, a lithium disilicate based glass-ceramic is produced by Alstom[++] for use in transparent armor systems.[4] Glasses and glass-ceramics have the overall advantage of having lower cost than most other ceramics materials, the ability to be produced in curved shapes, and formed into large sheets.

2.3 Transparent crystalline ceramics

For advanced threats, transparent crystalline ceramics are used to defeat the projectiles. There are not many candidate ceramic materials, however, that are transparent. The three major candidates are aluminum oxynitride (AlON), magnesium aluminate spinel (spinel), and single crystal aluminum oxide (sapphire). There are advantages and disadvantages to each material.

2.3.1 Aluminum Oxynitride Spinel ($Al_{23}O_{27}N_5$)

One of the leading candidates for transparent armor is aluminum oxynitride (AlON). It is produced by Raytheon Corporation[+++] and marketed under the trade name Raytran. The incorporation of nitrogen into an aluminum oxide stabilizes a spinel phase. Due to its cubic crystal structure, AlON is an isotropic material that can be produced transparent as a polycrystalline material. A polycrystalline material can also be produced in complex geometries using conventional ceramic forming techniques such as pressing and slip casting. The green body is processed to transparency and polished. Some properties of AlON are listed on Table 1. The limitations of AlON are its high cost and the sizes that are currently available. Raytheon is currently investigating the scale-up and cost-reduction of aluminum oxynitride. (Section 5.1)

[+] Simula Technologies, 10016 South 51st Street, Phoenix, AZ, 85044
[++] Alstom UK Ltd., Research & Technology Centre Stafford, Staffordshire, ST17 4LN, England.
[+++] Raytheon Electronic Systems, Lexington Laboratory, 131 Spring Street, Lexington, MA 02421

2.3.2 Magnesium Aluminate Spinel ($MgAl_2O_4$)

Spinel is a transparent ceramic that has a cubic crystal structure and can be transparent in its polycrystalline form. Spinel produced by sinter/HIP, hot pressing, and hot-press/HIP has yielded transparent material. The use of a hot isostatic press has been shown to improve the optical and physical properties of spinel.[18] Table 1 shows properties of spinel. Spinel offers some processing advantages over AlON. Spinel powder is available from commercial powder manufacturers while AlON powders are proprietary to Raytheon. Spinel is also processed at much lower temperatures that AlON. The optical properties are better than AlON, with its IR cut-off at 6 um compared to 5.5 um and 6 um for AlON and sapphire, respectively.[5] Though spinel shows promise for many applications, it is not available in bulk form from any manufacturer, but there are efforts to commercialize spinel. (Section 5.2)

		AlON	Spinel
Density	g/cm^3	3.67	3.58
Elastic Modulus	GPa	315	277
Mean Flexure Strength	MPa	228	241
Weibull Modulus		8.7	19.5
Fracture Toughness	$MPa\sqrt{m}$	2.40±0.11	1.72±0.06
Knoop Hardness (HK_2)	GPa	13.8 ± 0.3	12.1 ± 0.2

Table 1: Selected mechanical properties of AlON and spinel

2.3.3 Single Crystal Aluminum Oxide (Sapphire - Al_2O_3)

Polycrystalline aluminum oxide is an armor ceramic material that is used in opaque armor systems. Aluminum oxide is transparent when produced in single crystal form. The material is grown using single crystal growth techniques such as HEM[6] by Crystal Systems Inc.[+] or edge-defined film-fed growth (EFG)[7] by Saphikon.[++] The crystal structure of sapphire is rhombohedral and its properties are anisotropic and vary with crystallographic orientation. Sapphire is currently the most mature transparent ceramic and is available from several manufacturers. The cost is high due to the processing temperature involved and machining costs to cut parts out of single crystal boules. Sapphire is a very high strength material, but the strength is very dependent on the surface finish. There are current programs to scale-up sapphire grown by the HEM or EFG processes. These issues, as well as, polishing concerns will be discussed in Section 5.

3.0 APPLICATIONS AND REQUIREMENTS

Common military applications for transparent armor are ground vehicle protection, air vehicle protection, personnel protection, and equipment (sensor) protection. There are also commercial applications such as riot gear, face shield, security glass, armored cars and armored vehicles.

3.1 Personnel Protection:

There are several applications of advanced transparent armor systems for personnel protection. Some transparent armor items are listed on Table 2.[8] Increased use of military forces for "operations other than war" highlights the need to protect forces involved in these peacekeeping missions. For these operations, protective equipment such as riot gear is needed. Laser threats are also significant, and protective materials and coatings are sought for these applications. Once again, improved ballistic protection and lighter weight are the major objectives and cost is a significant factor.

3.1.1. Face shields

Personnel protection for facial protection is one Army application that requires transparent armor. The Army Research Laboratory has recently completed a program to improve the current visor design.[9] The two end items identified for improvement were the riot visor and an explosive ordnance (EOD) visor. The goal for the riot visor was to improve the ballistic performance by 30 percent without increasing the weight of the system. The overall goal for the EOD visor was to

[+] Crystal Systems, Inc., 27 Congress St., Salem, MA, 01970
[++] Saphikon, 33 Powers St., Milford, NH, 03055

reduce the weight of the visor by 30 percent while providing equal protection. The current specifications for the riot visor and EOD visor are shown on Table 3.

TRANSPARENT ARMOR ITEMS
Advanced Bomb Suit
Riot Gear Ballistic Face Shield
Riot Gear Ballistic Body Shield
Body Armor Suit: Individual Countermine
Sun, Wind, and Dust Goggle
Advanced Laser Protective System
Advanced Protective Eyewear System
Special Protective Eyewear, Cylindrical System
Ballistic Laser Protective Spectacle

Table 2: Transparent armor items for individual soldier ballistic protection[8]

	V50 velocity w/ 17 grain m/sec, ft/sec	Approximate Areal Density lb/ft^2	Construction Front face to backing Inches
EOD Army/ PS820	2050 /625 (QA)	4.27	0.375 Acrylic/ 0.25 PC
Riot Visor	850/259	1.55	0.250

Table 3 Existing visor specification

3.1.1.1 Riot Visor

The riot visor is made from injection-molded polycarbonate that has an areal density of 1.55 lb/ft^2. The visor is designed to protect against large, low-velocity projectiles such as rocks and bottles, but also from small, high velocity fragments. Since the goal of this program was to improve the ballistic performance without increasing the weight, an all-polymer solution was sought. Previous investigations[10,11] in the 1970's had shown the promise of polyurethane as an armor material, but the optical properties were not sufficient for a transparent armor material. Improvements in the optical properties of the polyurethane by Simula warranted a ballistic evaluation.

Ballistic testing was conducted for the riot visor against a 0.22 cal fragment simulating projectile (FSP). A helium gas gun was used for velocities below 2000 ft/sec and a 22 inch-long, 0.223 barrel with a 1:12 twist was used for velocities above 2000 ft/sec. The results for the testing are shown on Figure 2. As can be seen, the SIM 2003 behaves better than either polycarbonate or acrylic (PMMA).[2] Overall, the polyurethane performed 30-35 percent better than polycarbonate on an equal weight basis. The conclusion was that with the improved optical properties of the SIM 2003, this material would be an excellent replacement for polycarbonate to reduce the weight of the system.

3.1.1.2 Explosive Ordnance Visor (EOD)

The other objective for the ARL program was to reduce the weight of EOD visors. Table 3 lists the specifications for the existing visor. The goal is to reduce the areal density of the current system using different materials and constructions. Several constructions were investigated, including plastic/plastic laminates, glass/plastic laminates, and glass-ceramic/plastic laminates.[9] The plastic hard-face did not deform the FSP, while the glass and glass-ceramics were able to deform the FSP. Table 4 lists the results of the ballistic testing. Many of the constructions were better in weight than the current system weight of 4.27 lb/ft^2. The use of Sim 2003 generally increased the performance of the system. The optimum constructions used fused silica, Vycor, or TransArm, a transparent glass-ceramic.

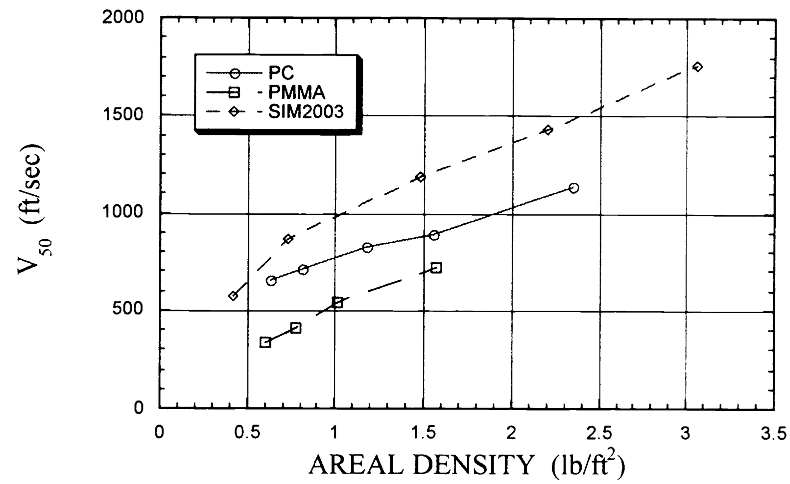

Figure 2: Results of the ballistic testing of the riot visor material

The ballistic data obtained in this investigation can be used for comparative purposes in designing a visor for use against the FSP threat for the range of areal densities tested. Other considerations are cost, availability, and manufacturability, for which there are trade-offs. For example, in visor applications, TransArm, Vycor, and fused silica performed well. TransArm is currently more expensive than fused silica. However, TransArm can be easily produced in curved shapes. Currently, it is difficult to obtain fused silica in a curved shape of a visor. Thus, while fused silica would be a cheaper solution that performs better (optically and ballistically) it may not be used for visor applications until the manufacturing problem of producing fused silica in curved shapes is overcome.

Armor system	V_{50} (ft./sec)	Approximate Areal Density (lb/ft^2)
PU Laminate	1995	4.25
PU Laminate	2021	3.84
PU Laminate	2510	5.2
Optimize PU laminate	-	3.15-3.25
SLS glass/PC	2001	3.67
SLS Glass/Sim 2003	2077	3.60
Vycor/PC	1962	3.14
Vycor/PC	2178	2.99
Vycor/Sim 2003	2172	3.06
Vycor/Sim2003	2261	2.97
Fused Silica/PC	2097	3.14
Fused Silica/ SIM2003	2244	3.17
Fused Silica Sim2003	2484	2.98
TransArm/Sim2003	2362	3.59
TransArm/Sim2003	2379	3.31

Table 4: Results of ballistic testing for EOD requirements

3.2 Ground Vehicles:

Ground vehicle protection is required for equipment that is used on the battlefield, such as HUMVEES, tanks, trucks, and resupply vehicles. Transparent armor is necessary for the windshield and side windows. There are several general requirements for these applications.[12] One critical requirement is the ability to withstand multiple hits since most threat weapons are automatic or semiautomatic. The windows must also be full size so that the vehicle can be operated in the manner in which it was designed. A small window on a truck can increase ballistic survivability but can reduce operational safety if the driver does not have an appropriate field of view. The windows also need to be durable and withstand normal wear in non-combat situations and from user damage.

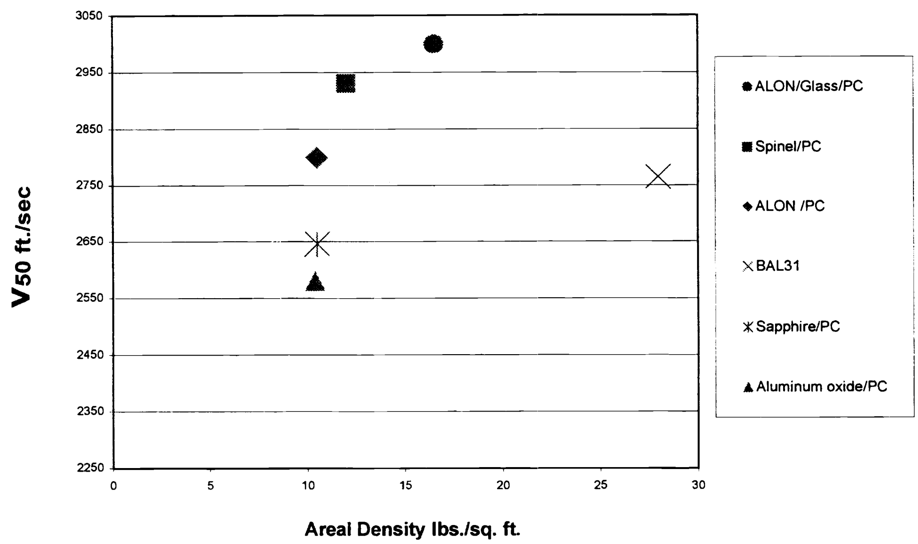

Figure 3: V_{50} versus areal density for various ceramic-based armor systems

The fielded systems fulfill these requirements with varying degrees of success. There are some requirements that future transparent armor systems need to address.[12] There is an overall requirement for future Army systems to be lighter. The weight of a transparent armor system is a parasitic weight for a vehicle. The added weight of a transparent armor appliqué can be significant, often requiring a beefed up suspension and drive train to maintain the vehicles performance capability. These upgrades also add weight to the system. Any weight savings improves the ability to bring the vehicle into theater. Reduction in weight increases the payload capacity for tactical vehicles and thus increases operational capabilities. Thinner armor systems are also required for similar reasons. Thinner windows can increase the cabin volume. Future systems also need to be compatible with night vision goggle equipment while offering laser protection.

Due to their size and shape, windows are constructed of glass and plastic. The major drive for new windows for these applications is lower weight and improved ballistic protection. Due to the number of these vehicles in service, the sizes of the windshields needed and the costs, improved glasses, glass ceramics and polymers are the materials of choice for these applications. Glass compositional variations, chemical strengthening, or controlled crystallization can improve the ballistic properties. Glasses can also be produced in large sizes and curved. Most importantly, glasses can be produced to provide incremental ballistic performance and incremental cost.

3.2.1 Improved armor for vehicular threats

There are a variety of threats that are encountered in combat and non-combat scenarios. The transparent armor solutions that were constructed and tested for use in visor applications are not applicable for all threats. Advanced threats require different solutions. The use of a transparent ceramic as a front-ply has been shown to improve the ballistic performance and reduce the weight of the system. Figure 3 is a chart of V_{50} versus areal density for transparent armor systems constructed with glass, sapphire, AlON, and spinel as a hard face and a polycarbonate backing. The BAL31 is a commercial glass/plastic laminate. One can see that the use of a ceramic front ply can reduce the areal density by as much as 65 percent. This is a significant weight savings over the state-of-the art. The ballistic performance of these transparent ceramics offers great potential for weight savings on future vehicles. Currently there are some challenges that must be overcome for these materials to be utilized. (Section 5)

3.3 Aircraft:

Air vehicles are materiel such as helicopters, anti-tank aircraft, fixed wing aircrafts, and airplanes that are used in combat or in support roles. Applications include windshields, blast shields, lookdown windows and sensor protection. The general requirements for these systems are similar to those for ground vehicles, though the importances of the requirements vary. Fielded systems are designed for use against 7.62 mm, 12.7 mm, and 23 mm HEI threats. Weight is a critical factor in these applications. The current transparent armor weight is the limiting factor for increasing ballistic protection. Heavier vehicles use more fuel, are more difficult to move into theater, and reduce maneuverability. The shields need to be full size and curved.

3.3.1 Advanced Lightweight Transparent Armor Program (JTCG/AS)

The Army Aviation Applied Technology Directorate has a program to develop advanced transparent armor for aviation applications. The program goals are to defeat a 7.62 mm PS Ball M 1953 with an areal density no greater than 5.5 pounds per square feet. This is a 35 % reduction in weight over current systems. The optical requirements are for a minimum 90 % light transmission with a maximum haze of 4%. There is some leeway in optical properties if significant weight reduction could be demonstrated. The second program goal is to defeat blast and fragments from a 23mm high explosive incendiary (HEI) projectile detonated 14 inches from the barrier. The areal density for this system is limited not to exceed 6 pounds per square feet. The efforts are ongoing and the results have not been published to date.

3.4 Other Applications:

3.4.1 Electromagnetic windows:

Many of the ceramic materials that are of interest for transparent armor solutions are also applicable to electromagnetic (EM) windows. However, there are many EM window applications where visible transparency is not critical. EM window applications include radomes, IR domes, sensor protection, and multi-spectral windows. The requirements for these windows vary greatly. There are some required properties mutual to many of the applications. The optical properties are extremely important for window applications. The transmission window and related cut-offs (uv, IR) control the electromagnetic regime where the window is operational. Other properties of interest are abrasion resistance, strength, and the thermal properties. The thermal stability of the materials properties are also critical if the material will be heated as in the case of missile windows.

3.4.2 Laser igniter windows

The Army is also investigating transparent ceramics for use as laser igniter windows for cannon applications.[13] The use of laser ignition has several advantages over conventional systems including increasing the firing rate and simplifies the gun design. This application requires efficient laser transmission to ignite the propellant. The optical and mechanical properties need to be able to withstand multiple firings. Since this is also a cannon application, the material must withstand flame temperatures near 2300 °C and pressures of 350 MPa for short durations. Sapphire and AlON have been tested for these applications. Sapphire performed well, while the AlON window cracked.

3.4.3 Artillery projectiles

Another Army application for EM window materials is for artillery projectiles. The two major requirements[14] are a low dielectric constant and a low loss tangent though the optical transparency is not important. Future artillery projectiles are being designed at higher muzzles velocities (Mach 3). Aerodynamic heating is a concern at these elevated velocities and the current plastic technologies will not survive in these environments. Mach 3 velocities can cause stagnation temperatures of

600 °F -700 °F (589 °K - 644°K). A prototype system utilized a nylon windshield with a Macor®* nose tip. It has a threaded window so that it can be screwed onto the nylon windshield. Macor® was chosen for its electrical properties, its high temperature capability, and its ability to be machined. The windshield was tested at 15000 g's for approximately 0.01 milliseconds and was able to survive with no permanent deformation. A replacement for the ceramic nose tip with a reduced dielectric constant and higher temperature capability is sought. The final design of the window must withstand 15,000 g's of inertial setback loads with 15000 rad/s2 of angular acceleration. The system must be capable of deploying at 650 m/s while spinning at 250 cycles per second.

3.4.4 Commercial Applications:

Many of these systems utilized for military applications would also have use in commercial systems such as law enforcement protection visors, riot gear, and windows in commercial car, trucks, and busses, as well as architectural requirements in certain buildings. The desire for armored automobiles for personal use is also growing. The cost/performance trade-off is not as critical since VIP protection systems can use more exotic and expensive materials to protect against significant threats.

4.0 DARPA/ ARL/ARO TRANSPARENT ARMOR MATERIALS WORKSHOP[15]

A workshop sponsored by the Defense Advanced Research Projects Agency (DARPA), the Army Research Laboratory (ARL), and the Army Research Office (ARO) gathered representatives from the materials research, materials processing, transparent armor testing and evaluation, and transparent armor user community to discuss transparent armor issues. Sessions addressed the history of transparent armor, the user requirements, materials development, finishing, and novel concepts.

Table 5 summarizes important performance requirements for a variety of military applications. A one (1) or two (2) rating was given depending on a strong or moderate correlation, respectively. The tailored ballistic performance, fragmentation reduction (multi-hit), and affordability were deemed to strongly correlate in importance to every application Weight reduction was also found to be very important, as was multifunctionality. Table 6 summarizes the critical technologies to address the performance requirements. The relative importance here varies more but the front-face, and backing material development was found to be very important, as are design models and manufacturing.

The results of the Transparent Armor Materials Workshop identified and documented the requirements and the technology shortcomings for transparent armor to be utilized against advanced threats. Many of these shortcomings have to do with the processing and manufacturing of materials, thus heavily influencing the final cost.

5.0 SELECTED CURRENT EFFORTS IN TRANSPARENT ARMOR CERAMICS

Previous sections have discussed the improvement in ballistic performance and weight reduction obtainable with the use of transparent ceramic and polymeric materials. Materials issues must be overcome for application into armor systems. The major limitations are commercial availability, the shapes and sizes available, and the cost. Most window applications require large transparencies on a scale greater than 12 inch by 14 inch, with thickness between 0.25" to 1". These sizes are difficult to obtain and have been the major limiting factor for use. There is a current deficit in the capital equipment (furnaces) that is available to produce larger sizes. Though improvement in ballistic performance has been shown, multi-hit capability has not been characterized due to the unavailability of large windows. Sapphire and AlON can be produced in larger sizes while spinel is limited to 5.25 square inches. The cost is very high for these materials due to the high purity powders necessary, high processing temperatures, long processing times, complex processing, and high machining and polishing costs. There are several ongoing programs to reduce these impediments for use of AlON, spinel and sapphire in military applications.

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* Corning Inc., One Riverfront Plaza, Corning, NY 14831.

Requirements / **Applications/Systems**	Tailored Ballistic Performance	Weight Reduction	Multi-Functionality	Larger and Curved Shapes	Fragmentation Reduction (Multi-hit)	Affordable Acquisition & Life Cycle Costs
Individual Soldier Face Shields & Bomb Suits	1	1	2		1	1
VIP Vehicles	1	2	2	2	1	1
Army Ground Vehicles Near Term	1	2	1	2	1	1
Vehicles Army After Next	1	1	1	1	1	1
Helicopters	1	1	1	1	1	1
Cargo Aircraft	1	1	1	1	1	1

Strong Correlation-1 Moderate Correlation -2

Table 5: Transparent armor requirements for military applications[15]

Requirements / **Technology Needs**	Tailored Ballistic Performance	Weight Reduction	Multi-Functionality	Larger and Curved Shapes	Fragmentation Reduction (Multi-hit)	Affordable Acquisition & Life Cycle Costs
Better Facing Materials Synthesis	1	1	2	2		1
Improved Ply and Backing Materials	1	1	2	2	1	1
Design Models for Multi-component Systems & Various Architectures		2	1		2	2
Testing Protocols: Non-arbitrary Multi-hit Standards Edge Effects, etc.	1		2		1	
Increased Defeat Mechanisms Knowledge	2	2	2	2	2	
Manufacturing and Finishing Processing Technologies	1	2		1		1

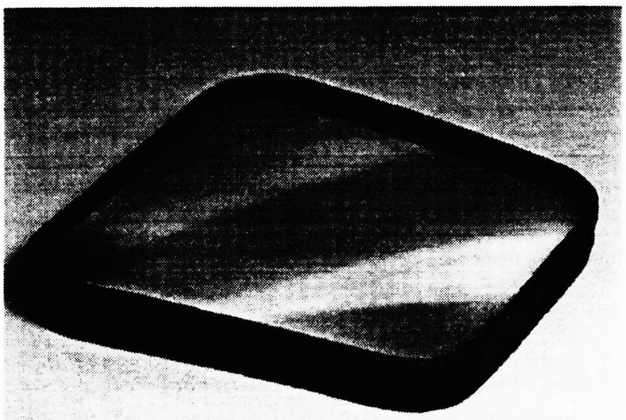
Strong Correlation-1 Moderate Correlation -2

Table 6: Transparent armor requirements and technology needs for advanced threats[15]

5.1 Aluminum Oxynitride Spinel (AlON)

Raytheon Corp has produced an 11 in. x 11in. curved AlON window (Figure 4A). The Air Force Research Laboratory (AFRL) is currently funding Raytheon to investigate cost reduction of AlON to produce larger windows. This will allow Raytheon to scale-up AlON so that it can be produced in large sizes at reasonable costs. Additionally, funding is sought to address the equipment issues to produce very large size plates.

Concurrently, the Army Research Laboratory is investigating transient liquid phase sintering of aluminum oxynitride to reduce processing costs.[16] A reaction sintering technique with the aid of a reactive liquid is the focus of the research. Small samples (Figure 4B) with a transmission of 85% and a haze of 14 % have been produced. The reduction of the haze and size scale-up are the immediate objectives of the program. ARL also has a SBIR solicitation for processes that can produce affordable aluminum oxynitride powders using scalable methods.



(A) Raytheon ALON (11" x 11")

(B) ARL AlON (3mm thick)

Figure 4: Photographs of aluminum oxynitride produced by Raytheon (A) and ARL(B)

5.2 Magnesium aluminate spinel (spinel)

Ceramic Composite Inc.[+] is currently investigating hot pressing of magnesium aluminate spinel under a Phase I SBIR sponsored by the Army Research Laboratory. Previous investigations have studied sinter-hot isostatic pressing (HIP) techniques. Hot pressing was chosen for this program as the processing technique based comparative analysis of the several processing techniques for producing spinel.[17] The research has focused on hot pressing with additive and hot-press/hot isostatic pressing (HIP). Hot pressing has been shown to be a successful technique to produce transparent parts. Figure 5 is a four-inch diameter, 0.44-inch thick spinel plate that has been produced using this technique. The plate has an 83 percent transmission with 9.32 percent haze. Scale-up to ten inch parts is underway using the hot-press technique. Subsequent HIPing has been shown to improve the optical properties and mechanical properties of spinel.[18] Hipping is generally not cost-effective and its use should be minimized. However, the improvement in the mechanical and optical properties may deem HIPing necessary for given applications.

[+] Ceramics Composites Inc., 110 Benfield Blvd., Millersville, MD, 21108

Figure 5: A hot pressed four-inch diameter, 0.44" thick spinel plate produced at ARL

5.3 Single crystal aluminum oxide (sapphire)

Sapphire is the most mature of the transparent ceramics due to its applicability in EM window and in the electronic/semiconductor industries. Sapphire with varying optical quality is produced by a various manufacturers. Crystal Systems Inc. is currently scaling their sapphire boules to 13-inch diameter and larger. Though this material has excellent optical properties, its high cost makes it problematic for use in transparent armor systems with possible exception in executive protection. The costs are driven from the processing technique and from the machining costs to cuts samples from a large boule.

Another manufacturer of sapphire is Saphikon, Inc., which produces transparent sapphire using an edge, defined growth technique. This produces an optically inferior material than Crystal Systems, but the cost for these sheets is significantly lower. The process size limitation is currently at 0.25 in. thick, in 12 in. x 15 in. sheets. The Army Research Laboratory is currently investigating use of this material for transparent armor systems using synergistic approaches in laminate design and construction. The current objective is to determine a baseline of glass/plastic and ceramic/plastic against the specified threat. Once the baseline is completed, sapphire will be tested in different constructions and compared to the baseline.

Scale-up to larger size poses several problems. The large sizes generally cost more to produce due to the difficulty in scale-up. Also, larges plates are more difficult to polish than smaller plates. Materials Systems Inc.[**] is investigating bonding sapphire plates using proprietary glass and glass-ceramic bonding materials. To date, bonds have been produced that are 70 percent of the strength of unbonded material.[19] This innovative technique offers the ability to make very large windows that may not be achievable in monolithic parts due to lack of capital equipment.

5.4 Machining and Polishing

Regardless of the ceramic material utilized, machining and polishing costs can be significant. The high hardness of AlON, spinel, and sapphire require diamond grinding and polishing media. The finishing process times are also quite long. Finishing costs can be as much as 50 percent of the final cost of the materials. These costs are greater for curved windows.

There are some programs to reduce the costs of machining and polishing. The Center for Optics Manufacturing[*] is investigating advanced grinding and polishing techniques for optics. Their methods have been shown to remove AlON,

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[*] Center for Optics Manufacturing, 240 east River Road, Rochester, New York, 14623

sapphire, and SiC at removal rates of 3 um/min, 1.5 um/min, and 0.5 um/min, respectively.[20] The Army Research Laboratory is also is looking for low cost solutions to polishing. An SBIR solicitation has been released for potential solutions. The overall objective for the SBIR solicitation is to find methods whereby a ground ceramic part can be processed (e.g., advanced polishing, coating) to transparency. The goal is to reduce the cost of the conventional polishing techniques currently being utilized.

6.0 CONCLUSIONS:

There is a general push to reduce the weight of military systems. Increased weight reduces maneuverability, transportability, and increases operation costs. One approach to reduce weight is to reduce the weight of armor systems. In addition to reduction of weight, new systems are required to defeat more advanced threats and to perform in combat and non-combat scenarios.

Advances in polymeric materials utilized for transparent armor systems have led to a renewed interest in these materials to reduce the overall weight of armor systems. Polyurethane has been shown to improve the performance as compared to polycarbonate backing. Evaluations are ongoing for varying threats and the results should be available in the near future. Transparent ceramics have been shown to offer significant ballistic protection with reduced weights over conventional glass/plastic systems. Advances in the processes of these ceramics and scale-up have lead to increased interest in using these materials for transparent armor applications

There are several programs that are investigating the cost reduction and scale-up of these materials. Successful outcomes from these programs should initiate their use for armor applications and fulfill the requirements to reduce weight on Army systems.

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