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Ballistic Performance of Ceramic/S_2-Glass Composite Armor

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Abstract

Ceramic composite armor was initially developed during the Vietnam War for use as helicopter armor and personnel armor. The requirements for the armor were light weight and the capability to defeat small caliber armor piercing (AP) projectiles. Several different ceramics were developed and tested for this application. It was found that aluminum oxide (Al_2O_3), silicon carbide (SiC) and boron carbide (B_4C) had the best combination of properties to meet the requirements. The long term goal of this research is to develop domestic knowledge, design and production capability of ceramic composite armors. In this present research, the relationship between the ballistic performance and mechanical properties of ceramic armor composites were investigated. The armor composite consisted of a 100x100 mm^2 commercial monolithic ceramic front tile; i.e. sintered Al_2O_3, sintered SiC, or hot-pressed B_4C bonded with an S_2-glass reinforced polymer composite (GRPC) backing plate. The ballistic test was performed against 7.62 mm projectiles (M80 Ball) in the velocity range of 800-970 m/s. A linear correlation between the areal density of armor and the V_{50} results was illustrated. The V_{50} ballistic limit values for the Al_2O_3, SiC and B_4C composite armors, calculated via U.S. Mil-Std-662F, were found to be 913 m/s, 869 m/s, and 829 m/s, respectively. High-speed photographic images captured during ballistic testing revealed the transition from dwell to penetration by the 7.62 mm projectiles. The complete penetration of all the armor composites was found to have occurred in approximately 200 microseconds. Furthermore, the relationship between the volume of the cone crack and mechanical properties were examined. The fracture toughness values of Al_2O_3, SiC, and B_4C were 4, 4.6, and 2.9, respectively. The volume of the cone cracks formed on the ceramic front tile plates increased with an increase in the fracture toughness of the ceramic materials.

Key words: V_{50} ballistic limit, Areal density, partial penetration, complete penetration

Introduction

The ballistic performance of ceramic materials used in armor applications is well known and has been extensively studied since the 1960s.(1–10) Advanced ceramics are one of the most important components of modern armor systems. Commonly used ceramic materials for this application are aluminum oxide (Al_2O_3), silicon carbide (SiC) and boron carbide (B_4C).(11) Integral to the armor structure is a ductile backing plate, which for example can be metals such as steel, aluminum or composites such as Kevlar or glass fiber reinforced plastics (GFRP). The purpose of the backing is to arrest the fragments of the projectile/armor and to absorb the remaining kinetic energy.(12) As backing plates, glass fibers (S_2-glass, E-glass) are being employed with epoxy resin systems to create composite backings that have high tensile and compressive strength, good energy absorption properties and relatively lower costs.

The mechanisms of ballistic protection for ceramic and metal armor are significantly different. Ceramics absorb the projectile kinetic energy through several mechanisms, including fragmentation, twinning, wave scattering and frictional means. Ceramics assist to defeat projectiles by overmataching the projectile in terms of elastic modulus, hardness and compressive strength. The phenomenon called interface defeat is where the impacting projectile flows radially outward (erodes) along the surface of the target, usually ceramic, with no significant penetration. An important component to interaface defeat is dwell, where the projectile is in contact with the target but has not yet begun to penetrate it. During dwell the projectile loses kinetic energy due to mass loss and deceleration. Metal armors

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absorb the projectiles kinetic energy by plastic deformation mechanisms, such as dislocation generation and motion, as well as twinning.

Ceramic armor systems are designed based on the requirements of threat performance, weight, application and manufacturing ability. The specific system design, including material selection, dimensions and areal density, are elaborated on depending on the performance of the specific armor ceramic.(13-15) There are other properties of the armor system components that are necessary to consider during the system design. These properties include density and porosity, hardness, fracture toughness, Young's modulus, sonic velocity and mechanical strength. Any single property of the ceramic does not have a direct correlation with ballistic performance, because the failure/fracture mechanisms involved during ballistic impact are complicated and the crack formation caused by the various stress states occurs in an extremely short time. The micro structural features affecting the physical and ballistic properties strongly influence crack propagation mechanisms and ultimately, ballistic performance.

This research was initiated in order to develop armor parts and design capability domestically within Thailand. This research studied the performance of monolithic armor ceramic grade Al_2O_3, B_4C and SiC tiles bonded with an S2-glass reinforced polymer composite (GRPC) backing plate. The targets subjected to impact by 7.62 mm M80 ball projectiles in the velocity range of 800-970 m/s. The V_{50} ballistic limit performance of the armor composites after impact was observed.

Materials and Experimental Procedures

Armor Composition

The armor composite in this research consisted of a 100x100 mm^2 commercially available monolithic ceramic front tile; i.e. sintered Al_2O_3, sintered SiC, or hot-pressed B_4C bonded with a 13 layer S_2-glass reinforced polymer composite (GRPC) backing plate. A schematic drawing of the S_2-glass reinforced polymer fabrication technique used in this experiment is shown in Figure 1. The assemblies were approximately 120x120 mm^2 in size. The ceramic tile was glued to the backing using epoxy resin and then covered with polyurea having a thickness of 3 mm. An example of the ceramic S_2-glass composited armor is shown in Figure 2.

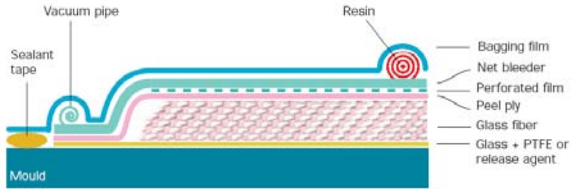


Figure 1. A schematic drawing of the S_2-glass reinforced polymer fabrication technique

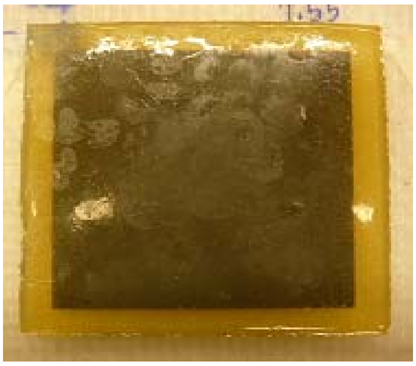


Figure 2. Example of B_4C / S_2-glass composite backed armor target

Ballistic Measurements

The ballistic testing was performed at the Royal Thai Air Force, Thailand, according to the U.S. Military and National Institute of Justice (NIJ) standards (MIL-STD-662E, NIJ Standard 0108.01). The testing was at level 3, which is 7.62 mm M80 ball ammunition and was conducted in the velocity range of 800-970 m/s. The experimental setup was created according to the guidelines given in the NIJ standard, as shown in Figure 3.

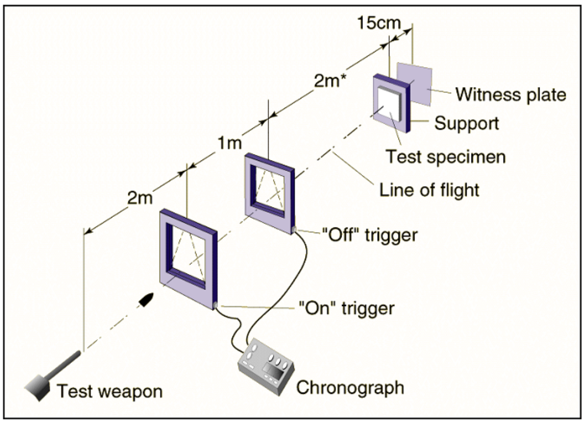


Figure 3. Schematic of the ballistic test setup

The bullet velocity was monitored and calibrated using a chronograph. A Fastcam-APX RS 250 KC image acquisition system was used to study the ultra-high-speed phenomenon of ballistic penetration. A recording rate of 20,000 frames per second and a shutter speed of 1/20000 second were programmed to record a sequence of separate images at prescribed time intervals. Images were acquired from the side view of the path of the projectile. The damage zones of the monolithic ceramic tiles, including ceramic fragmentation were observed by SEM and optically.

Determination of the V_{50} Ballistic Limit

V_{50} is often used for armor testing as a relatively quick method to acquire data on how effective the armor is against a specified threat or to rank armors against a threat. The V_{50} value also gives the designer a result that is representative of the armor at its breaking point. During V_{50} testing, each shot is counted as a separate statistical event. Individual shots are physically spaced far enough apart on a large target or taken against new targets, so that each new shot is considered to be taken on virgin material. This is opposed to a multi-hit pattern, where the panel is conditioned by previous shots, making subsequent shots easier to penetrate the target than previous ones. The following is an equation for calculating the V_{50} of a target configuration.

$$V_{50} = \frac{Sv}{Np + Nc} \quad (1)$$

S_V = sum of the striking velocities of all rounds in the zone of mixed results, m/s (ft/s)

N_P = number of partial penetrations in the zone of mixed results, dimensionless

N_C = number of complete penetrations in the zone of mixed results, dimensionless

Results and Discussion

The Physical and Mechanical of Monolithic Ceramics Armor

The physical and mechanical properties of the three commercial monolithic ceramic materials chosen for this study are listed in Table 1. In the proper configurations, SiC and B_4C tend to have the best performance for small to medium caliber threats, particulary armor piercing variants. Sintered alumina and more recently, sintered SiC, tend to be applied as a lower cost alternative to the more expensive hot pressed SiC and B_4C, when the threat may not be as severe.

Table 1. Physical and mechanical properties of the monolithic ceramics used in this work

Properties	Alumina	Silicon carbide	Boron carbide
Color	Ivory	Black	Black
Density (g/cm^3)	3.90	3.10	2.50
Flexural Strength(MPa)	379	550	350
Elastic Modulus (GPa)	370	410	450
Hardness (GPa)	14.4	28.0	30.0
Fracture toughness (MPa.m ½)	4.0	4.6	2.9
Fabrication Method	Sintered	Sintered	Hot Pressed

V_{50} Ballistic Limit and Areal Density

The results of the V_{50} ballistic testing are shown in Figure 4. When a projectile impacts a target, the result is scored as a complete penetration (CP) if the thin aluminum witness plate is penetrated or as a partial penetration (PP) if the witness plate remains intact. As the projectile velocity is increased, the projectile impact should ideally produce a transition from partial penetration (PP) to complete penetration (CP) within some critical velocity range. The critical velocity range may be quiet wide or narrow depending on the manufacturing tolerances of the targets. For this experiment, the V_{50} ballistic limit values for the Al_2O_3, SiC and B_4C composite armors were determined to be 913 m/s, 869 m/s, and 829 m/s, respectively. In accordance with MIL-STD-662F, the V_{50} value result for the B_4C target is acceptable with 3 PP and 4 CP within a velocity range of ~50 m/s. The V_{50} results for the Al_2O_3 and SiC targets are statistically weak, as there is only one recorded CP for both systems. Experimental limitations made it unfeasible to test a sufficient number of projectiles beyond 900 m/s to establish a statisically relevant V_{50} for both targets. The V_{50} of SiC may actually be found to be higher as the CP result is topped by 5 PP results obtained at much higher velocities.

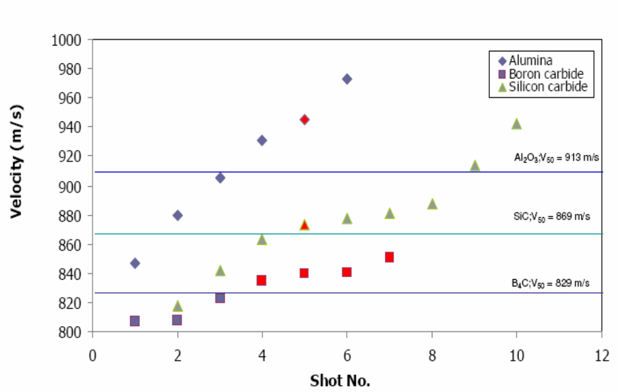


Figure 4. V_{50} ballistic limit results of monolithic ceramics with S_2-glass backing plate

Figure 5 shows the relationship of areal density and the resistance to penetration of the bullet. The Al_2O_3, SiC and B_4C tiles all have a thickness of 7 mm, resulting in differences in areal density. The sintered Al_2O_3 has the highest areal density, 4.64 g/cm^2, and was found to resist penetration up to a velocity of ~930 m/s. Sintered SiC has a moderate areal density of 4.00 g/cm^2, and was found to resist penetration up to a velocity of about 870 m/s. Hot-pressed B_4C, with the lowest areal density of 3.6 g/cm^2, was found to resist penetration up to a velocity of about 830 m/s. It can be observed that for this configuration, the ballistic performance increases as the density of the ceramic plate increases. This has previously been observed by other researchers.[16, 17]

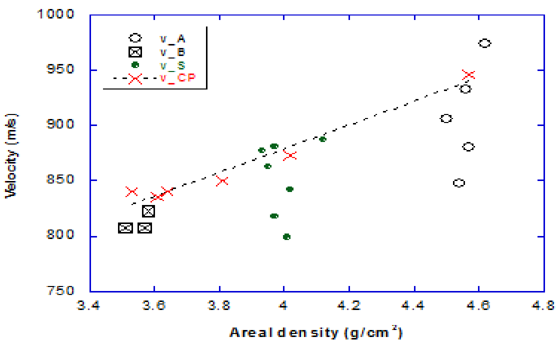


Figure 5. Areal density versus projectile velocity of the monolithic ceramic/S_2-glass composite targets

Projectile / Target Interaction Time

When the surface load generated by the projectile exceeds a critical value, at a critical impact velocity of the projectile, a transition between defeat and normal penetration behavior occurs.[18] Below this transition velocity the ceramic behaves as extremely strong, and above it behaves as significantly weakened. It is likely that the transition is related to the maximum accessible strength of the ceramic material.

The role of a ceramic tile in the defeat of a projectile is to overmatch the projectile, causing it to fracture, erode and decelerate. Thus, the longer the interaction time is between the projectile and the ceramic / target in general, the more energy that is absorbed and the greater the chance that the projectile will be defeated.

The projectile / target interaction time was calculated from the high-speed photographic impact sequences. The calculated interaction times for the ballistic tests are shown in Figure 6. It can be observed that most of the targets that were partially penetrated have interaction times above 800 μs. The targets experiencing complete penetration show interactions times of less than 200 μs. The impact sequence of a SiC/S_2-glass composite target impacted by a 7.62 mm projectile resulting in complete penetration is shown in Figure 7. The vertical red lines to the right of the target are fiducial marks. The sequence shows the projectile is just about to impact the target at 200 μs. By 250 μs a bulge is observed in the backing composite of the target. At 350 μs the composite backing has been penetrated and there is noticeable debris being ejected from the penetration hole in the backing plate. From 700 μs to 7450 μs the backing plate continues to expand and then retracts, due to the momentum imparted to the target

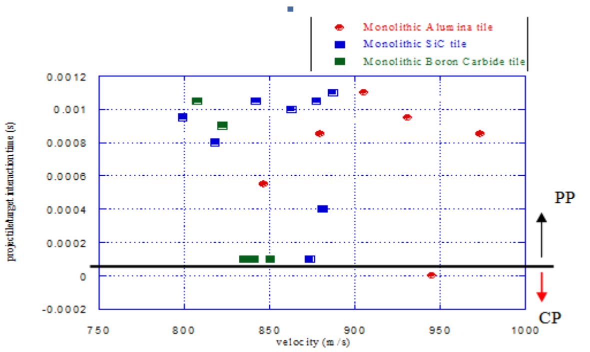


Figure 6. Projectile/Target interaction times. The transition from PP to CP of monolithic ceramics is also shown.

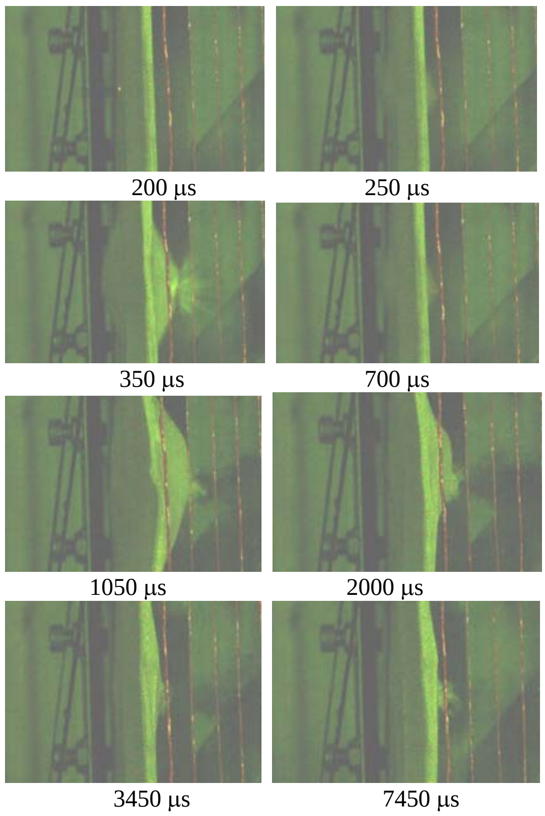


Figure 7. High-speed photographs of a 7.62 mm projectile penetrating a SiC/S_2- glass reinforced composite

Crack Formation and Debris Generation

When a target is impacted by the 7.62 mm projectile, several events are initiated simultaneously. Upon contact a stress wave is initiated in the projectile traveling towards the rear, while a stress wave is also created in the ceramic traveling towards the backing plate. As the sonic velocity of the ceramics is typically very high, on the order of 10,000 m/s, the wave reflects back and forth multiple times during the impact. These wave reflections generate tensile stresses, which if higher than the strength of the ceramic, will open up cracks. As the projectile continues to travel forward, the projectile tip is plastically deformed and begins to erode. Simultaneously, a fracture cone initiates in the ceramic at the interface between the projectile and the target. The cone that is formed spreads the load of the projectile onto a relatively wide area over the backing plate. This enables the energy of the impact to be dissipated by the plastic deformation of the ductile backing material. The backing plate yields at the ceramic interface. The tension that results in the ceramic as it follows the motion of the backing plate initiates axial cracks.[19-22]

Figure 8 shows the damage zone from the back face of the monolithic ceramic tile after the projectile impact. The images shown in Figure 8 are observed at the maximum projectile velocity that the targets could resist before complete penetration. The formation of a large central cone crack as well as tangential/ring and radial cracks in the Al_2O_3, SiC and B_4C tiles after impact were observed. For all of the ballistic impacts on the ceramic tiles, a locus of conoid coaxial cracks starts at the impact point and radial tensile cracks are initiated at the back surface close to the axis of impact.[23, 24] The number of tangential and radial cracks in the Al_2O_3 and B_4C tiles appears to be less than in SiC. The fracture toughness of ceramic, in addition to the projectile velocity, affects the cone crack formation. The highest volume cone crack appears in the SiC ceramic tiles, which also have the highest reported fracture toughness of the three ceramics studied. This observation is qualitative though.

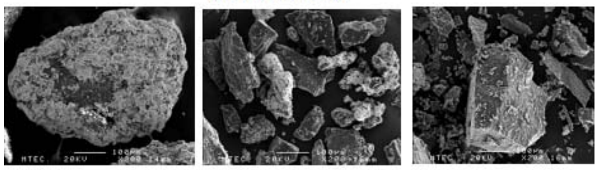
(a) (b) (c)

Figure 8. The damage zone of the ceramic plate after projectile impact (a) Al_2O_3, (b) B_4C and (c) SiC

Figure 9 shows the optical and scanning electron microscope images of the debris collected from ballistically tested Al_2O_3, B_4C and SiC. The debris was collected from the ceramic tiles that experienced partial penetration and hence effectively absorbed a large amount of ballistic energy. The debris, shown in Figure 9(a) is composed of various sizes ranging from large pieces of several mm to a fine micron sized powder. The debris from the Al_2O_3 appears to be the coarsest, which coincides with the relatively lower amount of macro cracks observed in Figure 8. The debris from the B_4C appears very mixed, with an equal amount of coarse chunks and fine powder. This may be related to B_4C relatively low fracture toughness. The collected debris of the SiC is fairly unform in size and smaller than the Al_2O_3. This again corresponds with the amount of observable macrocracks seen in Figure 8. The observed fracture mode of the finer debris formed during the impact appear to be transgranular fracture in SiC and B_4C. The Al_2O_3 appears to be more intragranular, likely due to the glassy nature of the grain boundary.

Al_2O_3 at 945 m/s B_4C at 850 m/s SiC at 873 m/s

(a) Optical microscope



Al_2O_3 at 945 m/s B_4C at 850 m/s SiC at 873 m/s

(b) Scanning electron microscope

Figure 9. Debris of the ceramic this after ballistic impact

Conclusion

The ballistic performance of targets comprised of Al_2O_3, SiC and B_4C ceramic tiles backed with an S_2-glass reinforced polymer composite plate were investigated.

- The V_{50} ballistic limit is defined as the velocity at which there is a 50% probability of specimen penetration. This method is intended for use in ballistic acceptance testing of armor and for the research and development of new armor materials, and is also very useful in designing armor with tailored thickness and weight for different levels of threat protection. The V_{50} ballistic results from the experiment found that Al_2O_3, SiC and B_4C/S_2-glass reinforced targets have V_{50} values of 913 m/s, 869 m/s, and 829 m/s, respectively. The measured V_{50} for B_4C is acceptable, while the V_{50} results for Al_2O_3 and SiC are statistically weak and need further testing before acceptance. This testing could examine reduced thickness or areal density of the S_2-glass backing plate.

- The ballistic testing created cone, tangential and radial cracks in the ceramic tiles. When observed at velocities before CP, the cracking appeared to be the most severe in the SiC. This may be related to the higher fracture toughness of the SiC. The ceramic debris of impacted tiles was also observed. Al_2O_3 tends to generate the largest sized debris, followed by the SiC. The B_4C debris was bimodal in nature. The observed fracture mode in SiC and B_4C was predominantly transgranular, as would be expected for hot-pressed B_4C and sintered SiC. The Al_2O_3 showed more intragranular fracture, as would be expected for sintered, glassy Al_2O_3.

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