Ballistic Evaluation of *TIMETAL*®6-4 Plate for Protection Against Armor Piercing Projectiles

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ABSTRACT
TIMETAL®6-4 (Ti-6Al-4V) plate 6 to 50mm (0.25 to 2in) thick was tested against various types of armor piercing projectiles, including 7.62mm (caliber .30) AP M2, 12.7mm (caliber .50) AP M2, 14.5mm API B32, and 20mm APIT. The alloy exhibited a very high ballistic protection mass efficiency; thus, substantial weight reduction can be achieved on ground combat vehicles by substituting titanium alloys for conventional metallic materials in ballistic protection systems. In this paper, results of ballistic tests are summarized, failure modes are described, relationships between the ballistic limit and plate thickness are provided, and example applications are discussed.

Key words: titanium, armor, ballistic, projectiles, Ti-6Al-4V

1. INTRODUCTION

TIMETAL®6-4 (Ti-6Al-4V) is an alpha-beta titanium alloy commonly used in numerous aerospace applications. Recently, interest in *TIMETAL*®6-4 for non-aerospace applications, particularly armor, has been increasing. This paper summarizes the results of ballistic trials on a wide range of thicknesses of *TIMETAL*®6-4 plate tested against standard armor piercing projectiles. Results for other titanium alloys, including *TIMETAL*®62S, *TIMETAL*®LCB, *TIMETAL*®35A and *TIMETAL*®550 are also included for comparison.

2. MATERIAL

Twelve heats of *TIMETAL*®6-4 at various thicknesses were evaluated in this program. Each plate was the product of a nominal 4500 – 5400 kg (10-12 klbs) vacuum-arc-remelted (VAR) ingot, except for one heat that was produced from an electron-beam-cold-hearth single-melt ingot (further information on this product is provided elsewhere [1]). The chemical composition ranges of the tested product are summarized in Table I. Material was converted to plate by a variety of processing routes, but all final rolling and heat treatment temperatures were below the beta transus temperature. Typical tensile mechanical properties of the *TIMETAL*®6-4 plates that were tested are summarized in Table II. Due to the use of lower cost unconventional processing routes, some of the plates had rather low tensile ductility. However, this did not appear to affect the ballistic performance against the armor piercing projectiles.

3. BALLISTIC TEST PROCEDURE

3.1 PROJECTILES

The projectiles used in this test program are summarized in Figure 1. Each of the projectiles consisted of a hard core plus ancillary components that serve interior and exterior ballistic purposes, as indicated schematically in the upper left-hand section of Figure 1.

3.2 METHODS

Ballistic testing was performed in accordance with standard military test procedures [2]. The test range configuration is shown in Figure 2. Photoelectric screens, in conjunction with chronographs, were used to calculate projectile velocities at a point halfway between the muzzle of the weapon and the target. Testing was performed at zero degree obliquity under ambient conditions (21-24°C [70-75°F] and 35-75% relative humidity). The reported thickness for each plate is the average of the thicknesses measured at each corner of the plate. A 0.51mm (0.020 inch) thick 2024-T3 aluminum witness plate was placed 152mm (6 inches) behind the target plate. Any perforation of the witness plate was defined as a complete penetration of the armor sample.

3.3 ANALYSIS

Each test consisted of firing projectiles at various velocities then assessing whether a particular impact resulted in complete penetration (perforation of the witness plate) or partial penetration. The average of the velocities of the lowest complete penetrations and highest partial penetrations was then used to estimate the V50, which is the velocity at which a complete penetration and a partial penetration are equally likely to occur. An example of this calculation is included in Figure 3. The V50 is a convenient number to generate and is widely used to quantify the ballistic protection provided by a given type of armor against a given threat.

4. BALLISTIC TEST RESULTS

4.1 CALIBER .30 (7.62mm) AP M2

Results are given in Figure 4 (top). All of the *TIMETAL*® 6-4 plate that was tested exceeded the minimum required ballistic limits of the applicable specification [3].

Another alpha-beta titanium alloy, *TIMETAL*® 62S (Ti-6Al-2Fe-0.1Si), was also tested (additional information on this alloy is provided elsewhere [4]). The performance of this alloy was identical to that of *TIMETAL*® 6-4. *TIMETAL*® 62S was also tested with an addition of 0.7 weight percent boron, which resulted in the formation of TiB_2 fibers randomly throughout the matrix. It was thought that the presence of the ceramic might improve the ballistic performance; however, as may be seen in Figure 4 (top), no changes in performance were observed.

A metastable beta alloy, *TIMETAL*® LCB (Ti-6.8Mo-4.5Fe-1.5Al), was also tested. This alloy was heat-treated to a very high strength level (approximately 1450 MPa [210 ksi]). The ballistic performance of this alloy was below that of the alpha-beta alloys. The very high strength resulted in excessive back-spall formation.

Results are also included in Figure 4 (top) for a very low strength titanium alloy (*TIMETAL*® 35A, an alpha alloy) at an ultimate tensile strength of approximately 345 MPa (50 ksi) [5]; this type of alloy has reduced ballistic performance, apparently due to excessive radial flow of material away from the penetrator.

When all of the alpha-beta alloys (6-4, 62S, and 62S + boron) are considered together, there is an excellent linear fit (R^2=0.997) between plate thickness and V50.

The level of performance observed for the alpha-beta alloys represents a 30-40% improvement in areal density compared to RHA steel [6].

4.2 CALIBER .50 (12.7mm) AP M2

Results are given in Figure 4 (middle). All of the *TIMETAL*® 6-4 plate that was tested exceeded the minimum required ballistic limits of the applicable specification [3].

Another alpha-beta titanium alloy, *TIMETAL*® 550 (Ti-4Al-4Mo-2Sn-0.5Si), is included in Figure 4 (middle) for reference [5]. This alloy had ballistic performance similar to that of *TIMETAL*® 6-4.

Several titanium alloy plates 25mm (1 inch) thick were found in a commercial scrap shipment from the former Soviet Union. The plates were painted in military camouflage and one edge was formed and contained a series of fastener holes. Although the identity of the original part was unknown, the circumstantial evidence suggested that this plate had been part of an armored vehicle. Except for the slightly high vanadium content, the chemical composition (Ti-6.2Al – 5.1V – 0.14O), mechanical properties (ultimate tensile strength 1014 MPa; elongation of 8%) and microstructure were very similar to those of *TIMETAL*® 6-4. As may be seen in Figure 4 (middle), this material was found to have the same ballistic performance as *TIMETAL*® 6-4.

Results are also included for a very low strength titanium alloy (*TIMETAL*® 35A) at an ultimate tensile strength of approximately 345 MPa (50 ksi) [5]; once again, this type of alloy has reduced ballistic performance, apparently due to excessive radial flow of material away from the penetrator.

As was observed with the 7.62mm results, there is an excellent linear fit (R^2=0.987) between plate thickness and V50 for the alpha-beta alloys (6-4, 550, and the foreign armor component [6Al-5V]). This level of performance represents a 30-40% improvement in areal density compared to RHA steel [6].

4.3 14.5mm B32

Results are included in Figure 4 (bottom). There is an excellent linear fit ($R^2=0.961$) between plate thickness and V50 for the ***TIMETAL***® 6-4 in all of the conditions tested.

4.4 20mm M602

A V50 test was performed using this round against a 50.8mm (2 inch) *TIMETAL*®6-4 plate. The V50 was 791 m s^{-1} (2595 ft sec^{-1}). This result was considered favorable and represents a 40% higher mass efficiency compared to RHA steel [7].

5. FAILURE MODE OBSERVATIONS

5.1 PROJECTILES

In instances where the projectile remained in the target, the sharp point often remained intact. Even when the point fractured, the residual nose maintained a sharp edge. In some instances, particularly with the 14.5mm B32 ammunition, the projectile fractured laterally (as shown in Figure 5) but the point nevertheless remained intact.

5.2 ARMOR

5.2.1 *Raw Material*

Due to the usage of several different conversion routes, a variety of final microstructures were obtained. A detailed description of each condition will not be given here, but all microstructures were indicative of final processing below the beta transus temperature.

5.2.2 *After Ballistic Testing*

The cross-section of typical ballistic impact at a velocity near the V50 is shown in Figure 5. All of the ballistic impacts had some combination of the features shown in this figure; different features predominated depending on the particular velocity (relative to the V50) and projectile diameter (relative to the plate thickness). Typical features of an impact included the following: an impact crater on the strike face; a plug associated with adiabatic shear; a bulge on the back surface; and a back-spall. In general, maximum energy absorption by the material (i.e., impacts near the V50) was associated with a large impact crater and large back-spall; the ablation of the face material, ductile tearing of the back-spall, and bulging of the back surface appear to be absorb a large amount of energy. As impact velocities are increased above the V50 there is a greater tendency for failure by plugging (adiabatic shear) with fewer tendencies for cratering and back-spalling, this appears to be a less favorable failure mode. When any one failure mode predominates, this appears to be an indication of less favorable ballistic performance. For example, the very high strength alloy, *TIMETAL*®LCB, fails almost entirely by back spalling only. The very low strength material, *TIMETAL*®35A, fails almost entirely by excessive ductile radial flow of material. Both of these types of alloys had reduced ballistic performance in comparison to 6-4.

6. TRENDS

For the four types of armor-piercing projectiles tested, there are differences in projectile materials, hardnesses, and shapes. Nevertheless, the fundamental penetration mechanisms of each projectile appeared to be about the same when tested against *TIMETAL*®6-4 and other alpha-beta titanium alloys. Therefore – at least for these circumstances – the projectiles may be considered homologous.

A good linear correlation ($R^2=0.972$) was found between the V50 ballistic limit and the plate-thickness to projectile diameter ratio (t/d), as shown in Figure 6. Thus, a first approximation of the V50 can be obtained for a given plate thickness and threat provided that the projectile is reasonably homologous to those used in this test program.

7. LIMITATIONS OF THIS STUDY

1. All of the results reported or referenced in this paper are for monolithic plate. Titanium alloys may perform quite differently if used with additional armor materials on the front or back.
2. The results reported in this paper are provided for informational purposes only and should not be used for design. Any armor system should always be appropriately tested by the armor manufacturer or user prior to putting the system into service.

8. EXAMPLE APPLICATIONS

Titanium alloys provide a practical method for weight reduction on military ground vehicles. Lighter vehicles have better transportability (air and ground), portable-bridge crossing capability, fuel economy and maneuverability. Two programs that already utilize titanium in upgraded vehicles are the Bradley Infantry Fighting Vehicle (Figure 7) and the Abrams Main Battle Tank (Figure 8).

SUMMARY AND CONCLUSIONS

TIMETAL®6-4 (Ti-6Al-4V) plate 6 to 50mm (0.25 to 2in) thick was tested against various types of armor piercing ammunition, including 7.62mm (caliber .30) AP M2, 12.7mm (caliber .50) AP M2, 14.5mm API B32, and 20mm APIT. Observations may be summarized as follows:

1. A very good linear correlation was found between plate thickness and the V50 ballistic limit for each projectile.
2. The ballistic performance of *TIMETAL*®6-4 was very similar to that of other alpha-beta titanium alloys, including *TIMETAL*®550 *TIMETAL*®62S, and a foreign armor component (Ti-6Al-5V).
3. Alpha-beta titanium alloys appear to offer better protection than other types of titanium alloys against armor-piercing ammunition. Although the data available for other alloys is very limited, very high strength (*TIMETAL*®LCB) and very low strength (*TIMETAL*®35A) alloys have reduced performance compared to *TIMETAL*®6-4 and the other alpha-beta alloys.
4. Typical favorable failure modes included a combination of cratering, plugging, back-spalling and bulging.
5. A very good linear correlation between the V50 ballistic limit and the plate-thickness to projectile diameter ratio (t/d) was found.

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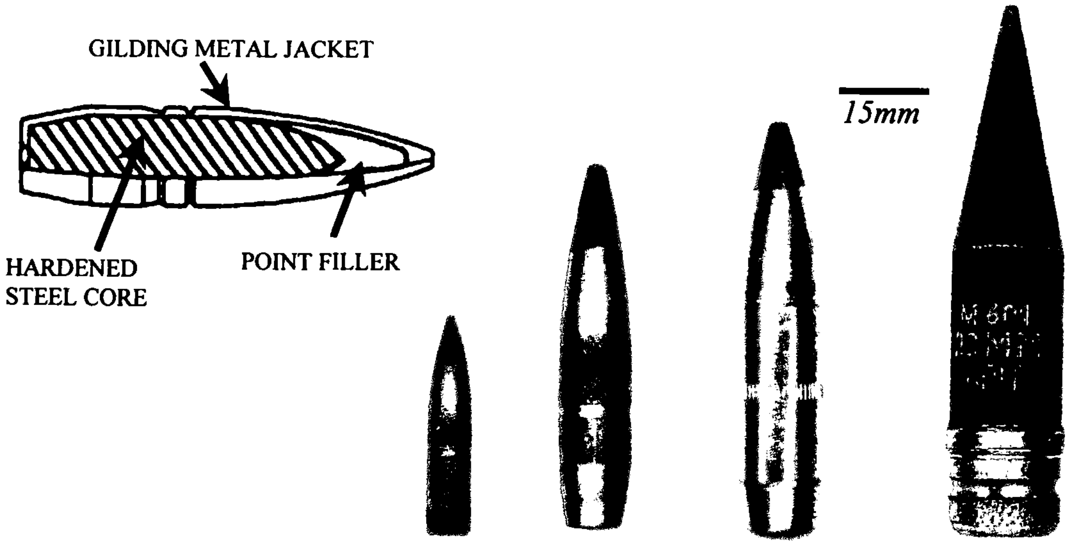
Table I. Summary of Chemical Compositions of 12 Heats of 6-4 Tested in This Program

Weight %	Al	V	O	C	Fe	N
Range	6.1 - 6.5	3.9 - 4.1	0.15 - 0.20	0.009 - 0.032	0.13 - 0.18	0.008 - 0.011
Average	6.23	3.93	0.17	0.023	0.160	0.011

Table II. Summary of Tensile Properties of 12 Heats of 6-4 Tested in This Program

	Orientation	Ultimate Strength, MPa	0.2% Yield Strength, MPa	Elongation, %
Range	Longitudinal	952 - 1034	834 - 945	5 -17
Average	Longitudinal	987.0	900.0	14.0
Range	Transverse	952 - 1076	834 - 993	3 - 18
Average	Transverse	1020.0	944.0	14.0



Designation:	.30 AP M2	.50 AP M2	14.5mm API B32	20mm APIT M601
Nominal Diameter:	7.62 mm	12.7 mm	14.5 mm	20 mm
Nominal Mass:	10.8 g	53.8 g	61.6 g	111 g

Figure 1. Summary of armor-piercing projectiles used in testing. Typical construction of 7.62 and 12.7mm projectiles is shown in the schematic diagram (upper left).

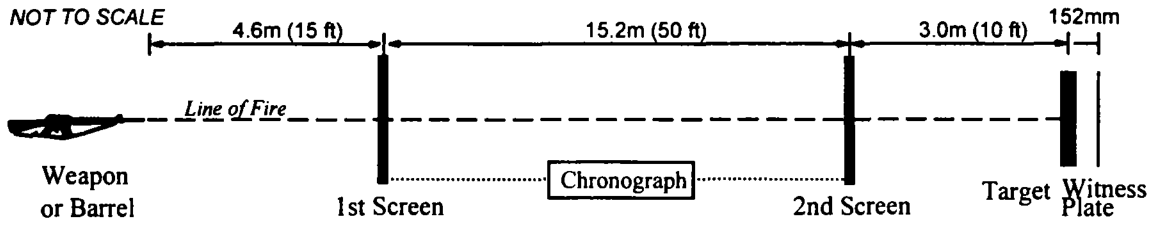


Figure 2. Test range configuration for ballistic limit testing of armor plates.

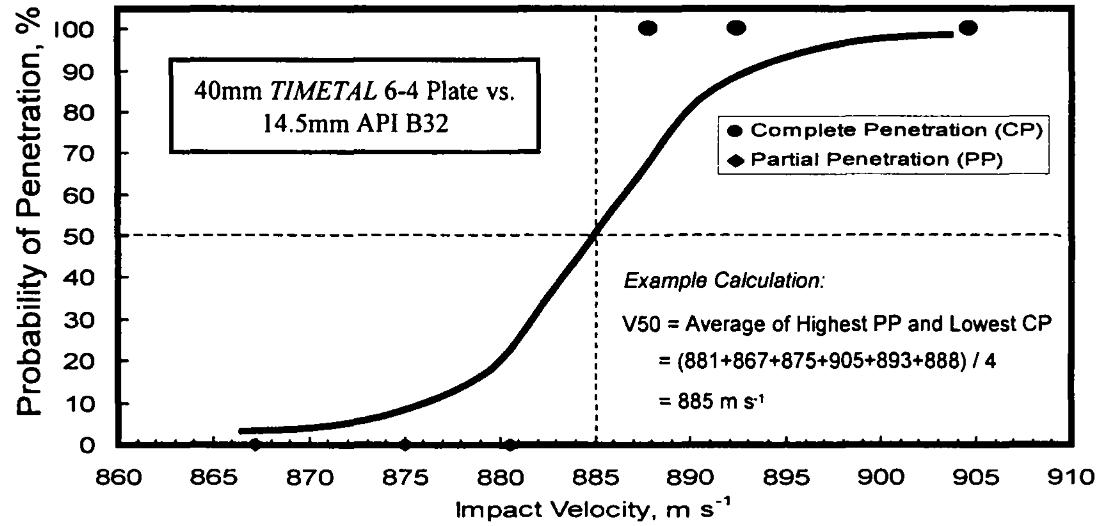


Figure 3. Probability of penetration versus impact velocity.

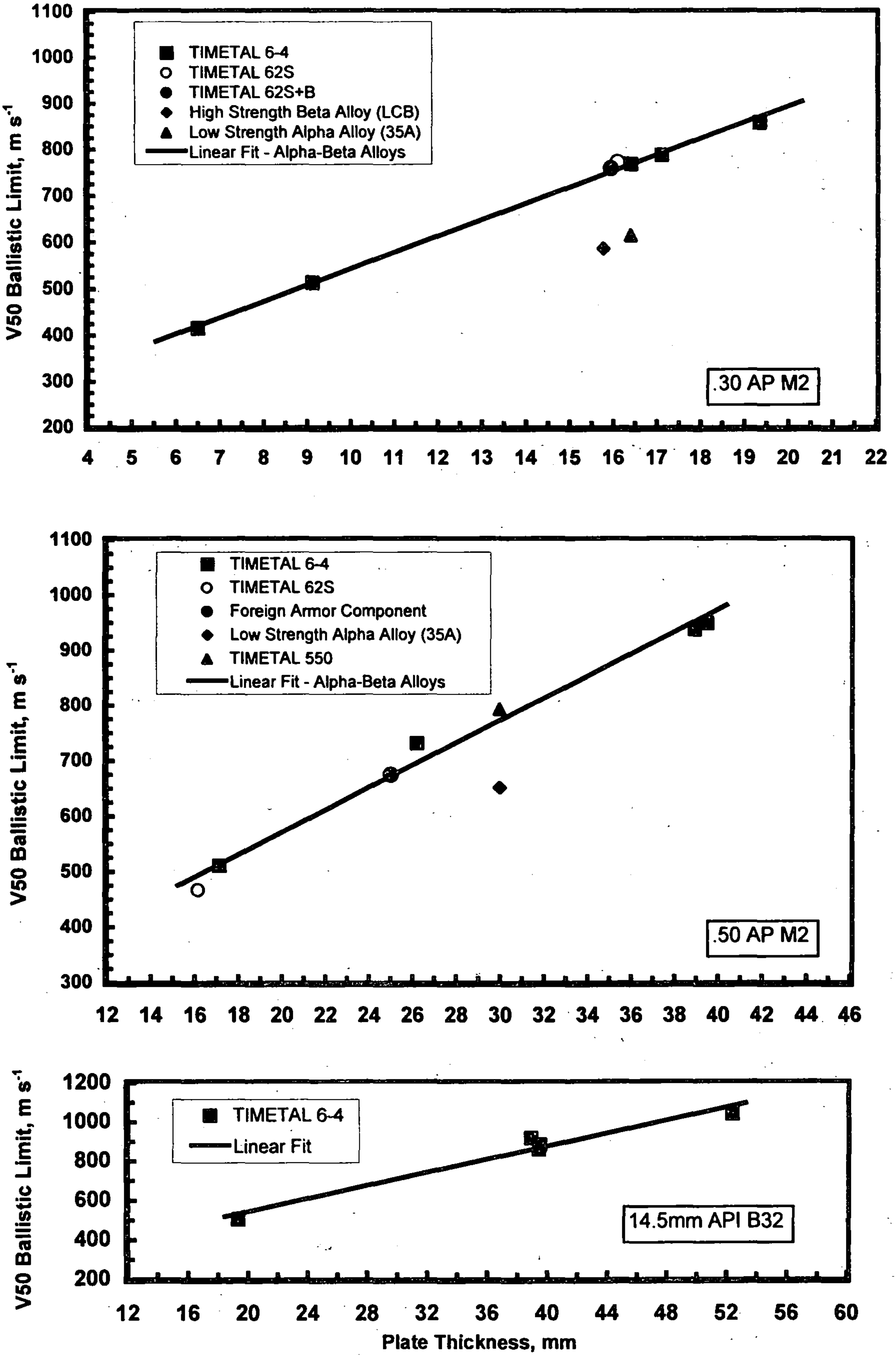


Figure 4. V50 ballistic limit vs. titanium plate thickness tested against .30 (7.62mm) APM2 (TOP), .50 (12.7mm) APM2 (CENTER), and 14.5mm API B32 (BOTTOM).

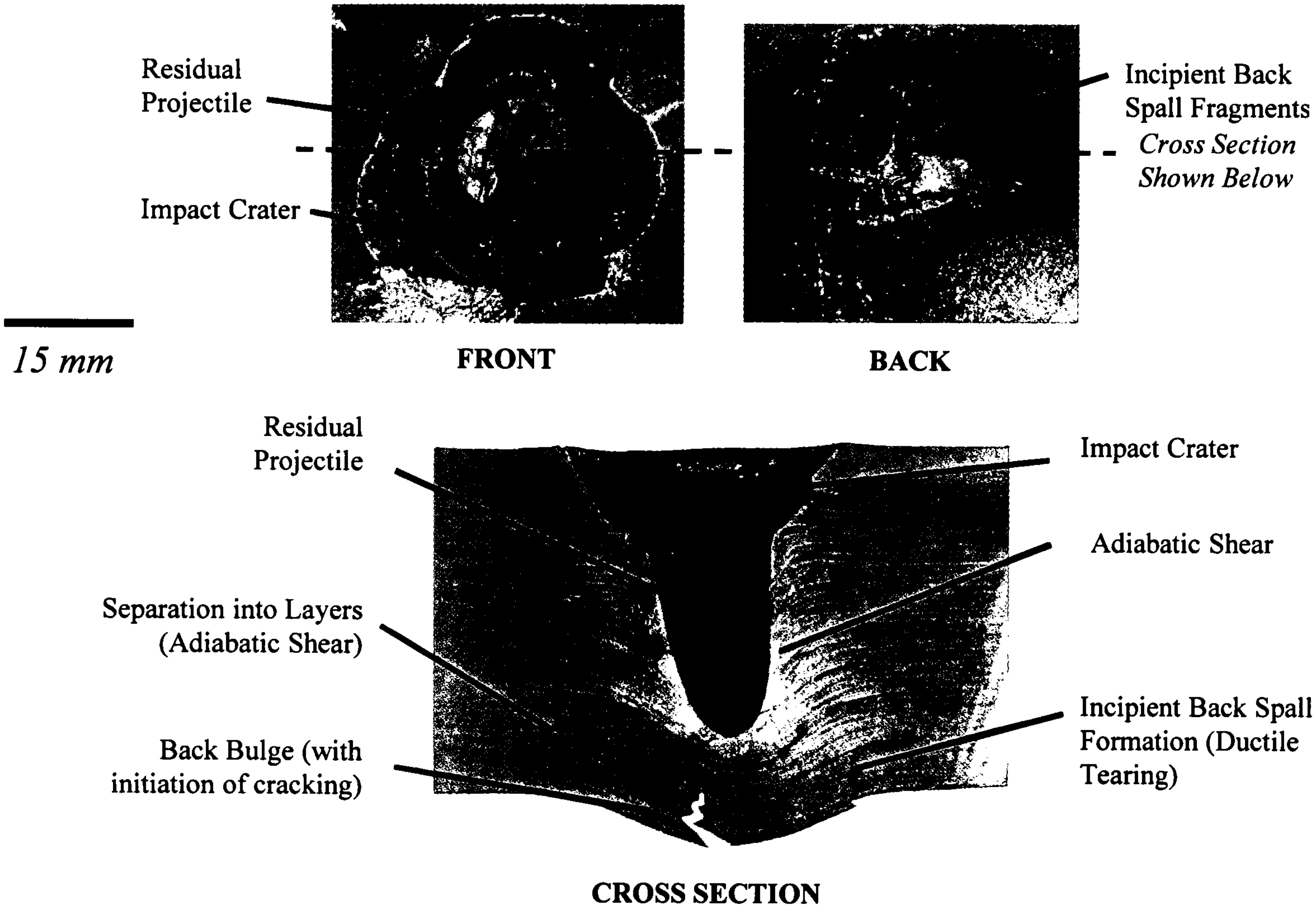


Figure 5. Front, back, and cross-sectional views of a partial penetration of 40mm (1.56in) *TIMETAL* 6-4 Plate by a 14.5mm API B32 projectile at 875 m s^{-1} (2871 ft sec^{-1}). This impact velocity was slightly below the V50 of 884.5 m s^{-1} (2902 ft sec^{-1}).

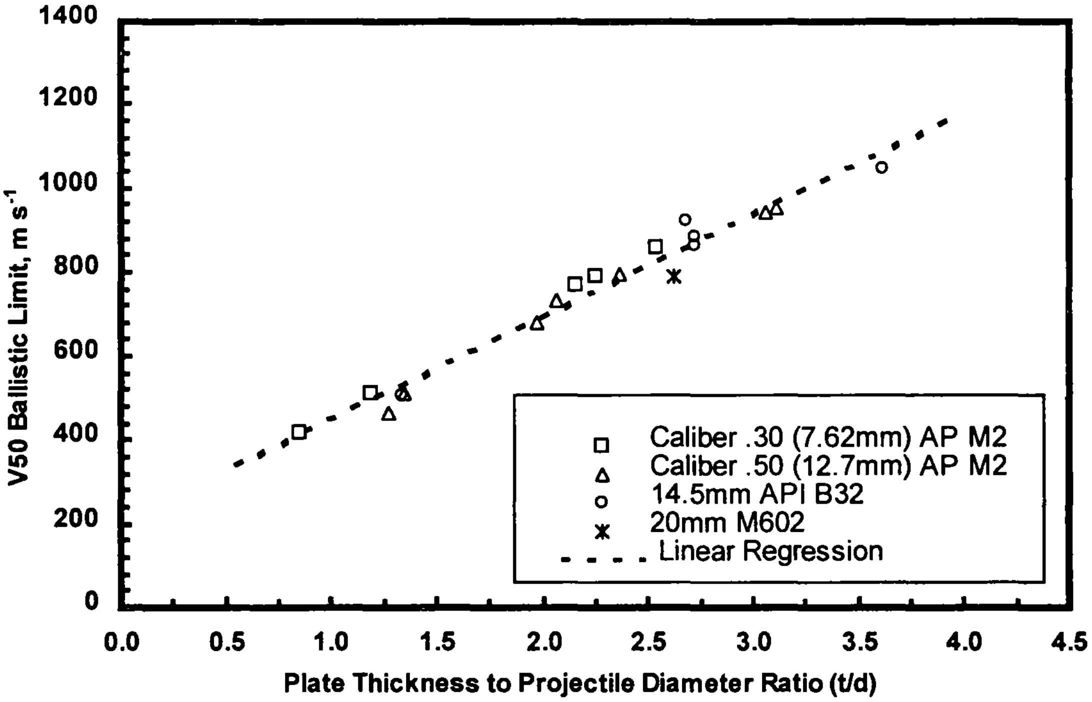


Figure 6. Effect of plate thickness to projectile diameter ratio on V50 ballistic limit for various armor-piercing projectiles against alpha-beta titanium alloy plate.

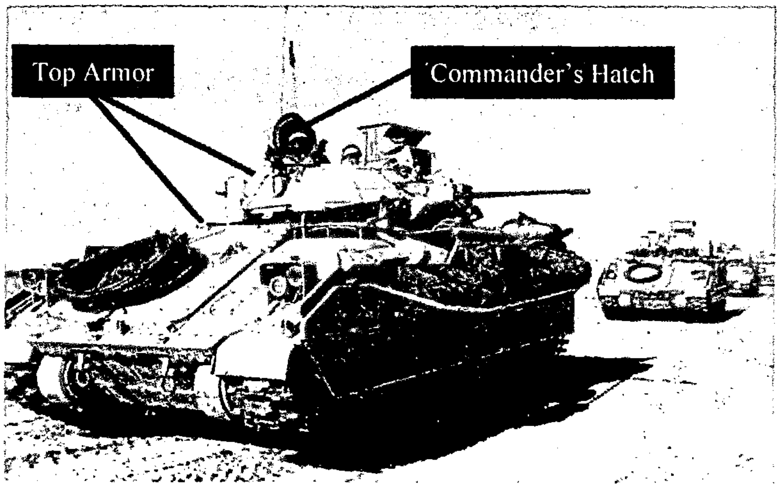


Figure 7. Example titanium alloy applications on the Bradley Infantry Fighting Vehicle.

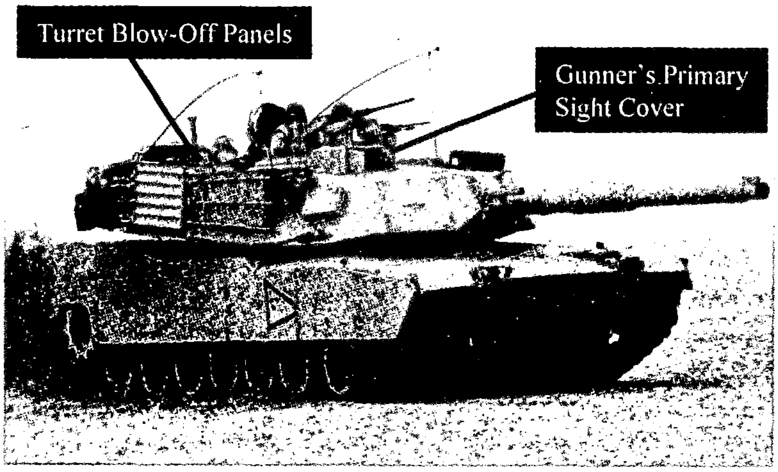


Figure 8. Example titanium alloy applications on the Abrams Main Battle Tank