Titanium Armor Applications in Combat Vehicles

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Titanium armor is being incorporated into the design of existing and future U.S. Army combat vehicles because it offers the best method of reducing vehicle weight and thus improving performance. Titanium's excellent specific mechanical and ballistic properties, as well as ease of fabrication, will likely make it a part of the U.S. Army's future combat system. How large a part it will be will depend on an overall cost/performance optimization.

INTRODUCTION

A paper published nearly four years ago[1] emphasized using low-cost titanium armors to replace rolled homogeneous armor (RHA) steel armor on existing U.S. Army ground combat vehicles and vehicles in development. Since then, Ti-6Al-4V has been applied to several Army systems: the commander's hatch and top protection armor on the M2 Bradley Fighting Vehicle (Figure 1), two components on the M1A2 Abrams Main Battle Tank (Figure 2), and the trails and recoil cylinders of the XM777 155 mm VSEL Ultralightweight Field Howitzer. Because of the Army's focus on the future combat system (FCS), the emphasis has been on new armors that will meet the anticipated ballistic threats

A kinetic energy ballistic threat has three components: the projectile, the striking obliquity, and the velocity. For shaped charges and blast-producing devices, the components differ: the type of warhead, the obliquity, and the stand-off distance define the ballistic threat. The 1997 paper showed that the strength-to-weight ratio and mass efficiency of Ti-6Al-4V allows a 30–40% weight reduction when replacing RHA steel armor while maintaining vehicle survivability. Mass efficiency (E_m) is the weight-per-unit-area of RHA required to defeat a given ballistic threat divided by the weight-per-unit-area of the subject material. Thus RHA has an E_m of 1 by definition. Titanium is interesting in that it maintains an E_m of 1.3–1.7 across a wide variety of threats. Other materials do not exhibit this property. For example, polymer-matrix composites can be very good against FSPs, but are notoriously poor against armor piercing (AP) threats.

Much research into titanium armor has been conducted during these past four years, with a dual focus: enlarging the ballistic database of titanium armor when impacted by threats other than small arms, and further reducing cost.

The cost-reduction efforts have been through various process changes. Titanium armor has been produced using single-melt electron beam cold hearth technology, and, separately, has been given various lower-cost thermomechanical treatments. The ballistic properties of each of these materials were evaluated to optimize cost and performance. There has also been a concerted effort to learn how to weld (and weld repair) thick titanium armor as would be used on a combat vehicle.

Figure 1. The M2 Bradley Fighting Vehicle.

Figure 2. The M1A2 Abrams Main Battle Tank.

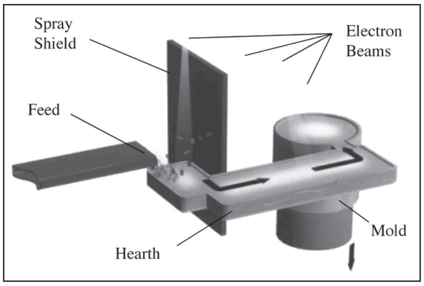

Figure 3. A schematic of the EBCHM process.

Recent work has also concentrated on titanium-encapsulated ceramics, which offer high mass efficiencies, but are expensive to produce. Current research is directed at improving this type of armor by elucidating the projectile-defeat mechanisms and decreasing costs.

BALLISTIC TESTING

A large database of titanium armor ballistic properties was created in the 1960s and 1970s. Because titanium was then quite expensive, it was envisaged as lightweight protection, so only the smaller ballistic threats were tested. These threats are fragment-simulating projectiles (FSPs), ball, and AP projectiles. FSPs, which attempt to simulate fragments from a high-explosive shell, cover a wide range of masses and kinetic energies. They are made of low-alloy steel with a hardness of 30 HRC. The smallest threat is a 2.54 mm 0.0875 g projectile travelling at subsonic velocities, while the worst-case threat is simulated by a 20 mm 54 g projectile travelling at 1,200 m/s. The term "ball" ammunition comes from the Civil War era and denotes a non-frangible lead ball. All military small-arms bullets have a full metal jacket of copper, gilding metal, or plated steel. AP projectiles, which arose shortly after the invention of the tank during World War I, consist of a core of hard steel or tungsten carbide covered with a full metal jacket as above.

These three types of smaller ballistic threats are used to evaluate an armor via a perforation test. A given armor is fired on with a particular threat at varying velocities. The velocity at which 50% of the projectiles perforate the armor is

Table I. Largest Contributors to the Cost of Titanium Alloy Armor Plate

Operation	Cost Type	Cost Reduction Strategy
Reduction of the ore	Energy	Scrap usage; direct reduction
Remelting	Energy	Cold hearth EB/plasma single melting
Reheating for rolling cooling	Energy	Ingot converted directly without complete
Annealing process	Energy	Eliminate by appropriate thermomechanical
Descaling	Capital, labor	Reduce number of reheating cycles

called the V_{50}, or ballistic limit velocity, and is a measure of the armor's performance. Details of this test may be found in Reference 2.

As the cost of titanium decreases, its use can be envisioned against larger ballistic threats. These threats include long rods, shaped charges, and mine blasts. Long rods are simply that: tungsten or depleted uranium alloy rods with an aspect ratio greater than about ten. The aspect ratio is usually quoted as length divided by diameter (L/D). Long rods are usually fin-stabilized subcaliber projectiles fired with a sabot, and possess very high velocities. Shaped charges are made of high explosive, shaped to focus the energy into a small spot on the armor. They are lined with a dense, ductile metal, usually copper, which forms a hypervelocity slug and assists in armor penetration. Explosively formed penetrators (EFPs) are similar to shaped charges, but penetration is performed solely by the hypervelocity slug. Mine blast is the most common combat vehicle threat, but the most difficult to quantitatively evaluate. These are generally buried, pressure-sensitive, high-explosive charges. The most important parameters are the size and type of the charge, the depth at which it is buried, and the type of soil above it.

The long rod and shaped charge ballistic threats are usually used to evaluate armor via a penetration test; however, perforation tests are sometimes used. Mine-blast testing is highly vehicle-structure dependent, and will not be covered here. There are several variations of the penetration test, but the simplest involves a semi-infinite armor plate. A ballistic threat is fired at the armor, and the depth of penetration (DOP) is recorded. This is then compared to the DOP of the same threat into RHA, and serves as a measure of performance.

Gooch et al.[3–6] have tested titanium 6Al-4V against laboratory-scale long-rod penetrators with L/D of ten, 13, and 20 and impact velocities up to 2,000 m/s. The penetrators were tungsten alloys with masses of 65, 162, and 105 gm, respectively. For the L/D ten and 13 rods penetrating semi-infinite stacks of titanium alloy plates, E_m starts at 1.7–1.8 at 1,000–1,100 m/s and decreases to 1.5–1.6 for velocities up to 2,000 m/s. When fired in a perforation test, the L/D ten and 20 rods gave similar mass efficiencies. Additionally, an L/D ten depleted uranium long rod was tested against semi-infinite stacks of titanium alloy plates and produced similar E_m results. This indicates that, for larger ballistic threats and thicker plates, titanium maintains the high mass efficiencies seen for smaller ballistic threats.

LOW-COST TITANIUM

In order of importance, the key contributors to the cost of titanium alloy armor plate are shown in Table I along with cost-reduction strategies.

Although each of these strategies is actively being pursued, converting the ingot directly without complete cooling is problematical in that the mills generally used for rolling are distant from the melting site, and that ingots are generally descaled before rolling. Following are discussions of electron-beam cold-hearth single melt and reduced thermomechanical processing.

Electron-Beam Cold-Hearth Melting

The product of an electron-beam cold-hearth single-melt (ECBHM) of Ti-6Al-4V plate was evaluated for application to army ground vehicles by Wells et al.[7] Single-hearth melting would considerably reduce the cost of titanium alloy plate because it would enable the use of lower-cost raw materials and, of course, only one melt.

The two basic types of cold-hearth melting for reactive/refractory metals are electron beam and plasma arc, similar processes with different heat sources. In both processes, the feed stock is first melted into a water-cooled copper hearth, then the molten metal passes into a refining stion, and finally over a small lip or weir and into an ingot mold, where solidification occurs. In the bath, the metal is kept molten due to surface heating by additional electron-beam guns in the case of EBCHM, or plasma torches. Solidification takes place in a water-cooled copper mold, where the resulting ingot is continuously withdrawn into a pit. Both processes can use a wide variety of raw materials including machining chips, revert scrap/croppings from rolling, forging and other primary processes, and sponge combined with master alloy.

In the electron-beam process, melting is done under a vacuum of 10^{-5} torr or better. Because elements with a high vapor pressure (such as aluminum) evaporate in the vacuum environment of the EB melt chamber, aluminum shot must be added to compensate for this loss. A schematic diagram of the process is shown in Figure 3.

Two companies now have EBCHM capability with ingot sizes up to 22,700 kg. Ingot length (and thus weight) is governed by the depth of the pit beneath the ingot mold. Both round and rectangular ingots may be produced. A common ingot size in commercially pure (CP or unalloyed titanium) grades is 66 cm × 132 cm × 400+ cm weighing 16,000 kg. These furnaces are capable of melting up to about 3,600 kg/h for CP grades and perhaps 2,300 kg/h for alloy grades.

A round 76 cm diameter ingot of Ti-6Al-4V weighing 3,994 kg was purchased from Titanium Hearth Technologies (now part of TIMET). This ingot was melted in a 3.2 megawatt furnace with five separate EB guns (three of 750 kw and two of 500 kw), with one focussed on the feed stock, one on the initial melt pool, two in the refining section, and one on the ingot mold.

The blend composition used to make this heat consisted of the following:

- 31.6% titanium sponge
- 62.4% titanium Ti-6-4 turnings
- Balance aluminium shot and V-Al master alloy.

During the melt, a sample of the hot metal was taken for chemical analysis every 12.5 cm along the ingot. The results are shown in Table II.

The ingot was first conditioned by turning approximately 6 mm from the surface and then rolled on conventional steel mill facilities according to the following schedule:

- Ingot heated to 1,150°C and rolled to a slab 21 cm thick × 103 cm wide ×

Table II. Chemical Composition of the Ingot, (wt.%)

Element	Al	V	O
Average	6.28	4.16	0.176
Std. Dev.	0.145	0.068	0.004
Max.	6.66	4.25	0.181
Min.	6.05	3.97	0.166
Range	0.61	0.28	0.015

Other Elements

Sn	Zr	Ni	Mo	Mn	Si	Cr	Cu	H	C
0.017– 0.019	0.022– 0.024	0.032– 0.035	0.026– 0.027	0.0 0.0	0.0 0.0	0.024– 0.036	0.001– 0.004	0.007– 0.010	0.024– 0.026

381 cm long.

- Cut into three sections and reheated to 940°C.
- Rolled to 25 mm, 38 mm, and 64 mm thick plates.
- Annealed at 940°C for two hours, roller leveled.
- Final mill annealed at 760°C for one hour.
- Each plate thickness cut into two pieces and finished by overall belt grinding.

This processing schedule resulted in an ingot-to-plate yield of about 71%. For larger production quantities and fewer rolled thicknesses, a yield from ingot to plate of close to 80% should be achieved. Yield is a very important factor in determining the final cost and, thus, price, of finished plate.

Two tensile-test specimens were taken from each end of each plate in both the longitudinal and transverse directions. All values exceeded the requirements of MIL-T-9046J, Grade AB-1, and MIL-DTL-46077F.

Ballistic testing was performed on the three plate thicknesses with 20 mm FSPs and 30 mm armor piercing discarding sabot projectiles. Ballistic testing was performed in accordance with standard military test procedures[2] to obtain V_{50} ballistic limit values. Ballistic test results are summarized in Table III. The expected values in Table III are the required passing values from MIL-DTL-46077F for the respective thickness. For comparison purposes V_{50} velocities are given for equivalent plates thicknesses of standard wrought product. It may be seen that the single-melt EB material compares very favorably with standard-wrought Ti-6Al-4V plate.

Table III. Ballistic Properties of EBCHM Ti-6Al-4V Plate and Other Sources

Thickness (mm)	Material	Test Projectile	Test V_{50} (m/s)	Expected V_{50}* (m/s)
25.35	EB Single Melt	20mm FSP	1016	950
26.72	Standard	20mm FSP	1023	1008
38.79	EB Single Melt	20mm FSP	1493	1362
38.30	Standard	20mm FSP	1496	1352
63.96	EB Single Melt	30mm APDS	932	889
63.83	Standard	30mm APDS	941	888

*from MIL-DTL-46077F

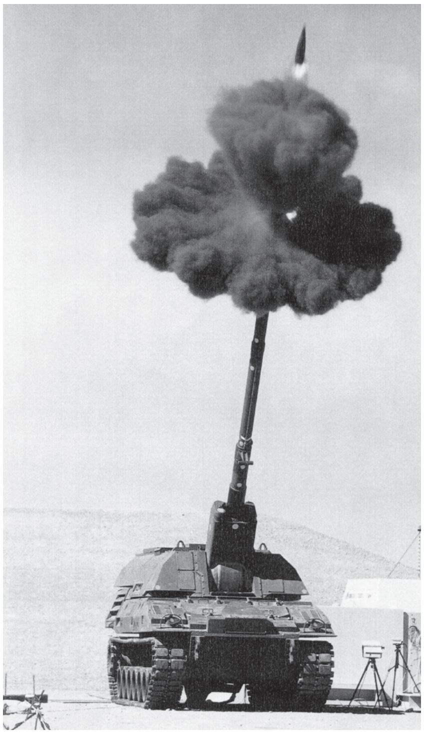

Figure 4. A prototype of the Crusader 155 mm self-propelled Howitzer.

Reduced Thermomechanical Processing

For structural applications, Ti-6Al-4V is normally solution-treated and aged; however, for armor applications, the best ballistic properties have been found to result from an annealed microstructure. Burkins et al.[8,9] examined the effect of annealing temperature on the ballistic properties of this alloy. A large plate 28.5 mm thick was produced by 1:1 cross rolling below the beta transus. The plate was then vacuum-creep flattened at 788°C to flatten and stress-relieve it, and test plates were cut from it. Ten of the test plates received an additional annealing and one did not. All 11 test plates were sandblasted and pickled to remove the alpha case. Ballistic limit velocity testing was performed with the 20 mm FSP at zero degrees obliquity. The V_{50} of all the plates were found to be about the same, as long as the annealing temperature was below the beta transus (996°C). The plates annealed above the beta transus had much poorer ballistic properties. The as-flattened plate had comparable properties to the plates annealed below the beta transus, which indicated that the annealing step could be omitted to reduce cost.

Following up on this, Burkins et al.[10] evaluated the effect of different thermomechanical processing schedules on the ballistic properties of Ti-6Al-4V. Plates were straight and cross-rolled above and below the beta transus, and given anneals above and below the beta transus. Additionally, one set of plates was given the standard STA treatment. The plates were ballistically tested with the 20 mm FSP as before, but also with the .50 caliber AP projectile. The results are given in Table IV.

Several conclusions may be drawn from these data:

- The FSP is a much better discriminator of the ballistic quality of the material than the AP projectile.
- Cross rolling is better than straight rolling.
- Alpha-beta rolling is better than beta rolling.
- No annealing is better than annealing.
- Alpha-beta annealing is better than beta annealing.
- Once the material is beta annealed, another alpha-beta anneal will not bring the properties back.
- As-rolled or annealed material is better than solution-treated and aged material.

Welding

Welding is the preferred method of fabrication when titanium is used for armor in ground systems, both for hull construction (integral) and applique. During the past several years much has been learned about welding thick-section components. Titanium is an extremely reactive metal and great care must be taken to exclude air from the molten metal pool to prevent pick-up of interstitial elements. However, production components are being produced (such as for the M1A2 Abrams main battle tank) on the same equipment used for steel fabrication, with the addition of inert gas shielding. Generally, argon-helium mixtures are used in the torch, in a secondary trailing shield, and also in a tertiary shield on the back side. The tertiary shield is only required on the first pass of a weld. General Dynamics and the Army Research Laboratory have conducted studies to understand how satisfactory, production-rate welding and field-repair welding can be accomplished on titanium armor plates. The effects of different cutting techniques, edge preparation, type of inert-gas shielding, and weld-metal chemistry on ballistic and mechanical properties have all been evaluated. High-deposition-rate welding processes have been developed for combat-vehicle production, but because of the complexity of inert-gas shielding, welding titanium will never be as easy and inexpensive as welding RHA. However, the cost is not prohibitive.

While Ti-6Al-4V is the alloy of choice for structural and applique armor for Army applications, welding procedures generally apply to both alloy and commercially pure materials. A preliminary investigation of three advanced titanium welding processes developed in the former Soviet Union was performed by the U.S. Army with the Navy.[11] All welds were made at the Paton Welding Institute, Kiev, Ukraine on commercially pure titanium plates. The object of this study was to evaluate the quality and mechanical properties of the welds and assess the applicability of these processes to army ground-vehicle production.

Battlefield repair of titanium armor, which will be required, should not rely on the extra logistics of inert-shielding gas. ARL has an ongoing contract with Edison Welding Institute, Dayton, Ohio, to develop field-repair welding processes of titanium with flux-cored electrodes without inert-gas shielding.

ENCAPSULATED CERAMICS AND SBIRS

In the past, most armor has been monolithic (i.e., a single material). The performance of armor can be increased by using separate materials to perform the separate functions of breaking up the projectile and catching the pieces. Ceramics, such as alumina, boron carbide, and silicon carbide are extremely hard, and will break up a projectile. Titanium armor is a very good backing material because of its high mass efficiency against a broad spectrum of threats. Because the ceramics are brittle materials, they fracture as they break up the projectile. It has been found that if ceramic fracture can be delayed by increasing confinement, performance can be increased. The highest degree of confinement is provided by encapsulating the ceramic plate into a jacket of the backing material. In the past, this has been done with alumina tiles and titanium. A hole is precision-machined into a thick plate of titanium armor the same size as the tile. The tile is inserted into the hole and a cover plate is mounted. The assembly is evacuated, the cover plate is electron-beam welded on, and the whole assembly is then HIPed. X-ray computed tomography (CT) is necessary to ensure plate quality before ballistic testing. Although the mass efficiencies of this kind of armor are high, it is very expensive and time-consuming to produce. There are a number of approaches to reduce the cost of this armor that are being pursued by the Army Research Laboratory. The simplest of these is direct casting of titanium around the tile. Another technique being pursued is to use powder-metallurgy techniques to hot-press titanium powder around the ceramic tile. Dynamet Technology, in Burlington, Massachusetts has an Army Small Business Innovative Research (SBIR) Phase II program on titanium alloy encapsulation of ceramic for ballistic armor applications. The company will apply its titanium powder-metal technology to advanced armor concepts aimed at defeating a medium-caliber threat. The technical approach involves Dynamet's CHIP process of cold isostatic pressing, vacuum sintering, and hot isostatic pressing to encapsulate ballistic-grade ceramic tiles with tough titanium alloys. The approach offers significant potential for increased penetration resistance through resulting hydrostatic confinement, and also provides a barrier to environmental and handling damage. The program involves an iterative approach to the armor development including designs established in conjunction with Army Research Laboratory, manufacturing by Dynamet Technology, ballistic testing at Army Research Laboratory, followed by analysis and design modifications. Improved vehicle maneuverability and range, greater crew safety, and improved armor-system durability are anticipated advantages of this technology.

Dynamet Technology also has an Army Phase 1 SBIR on lightweight durable titanium tank tracks using low cost powder metal titanium composite technology. In this Phase 1 SBIR program, a lightweight titanium track will be designed for combat vehicles such as the Crusader (Figure 4). Dynamet Technology, with expertise in titanium materials and manufacturing technology, will team with the Keweenaw Research Center at Michigan Technological University, which has expertise in tank track design, analysis, and testing. Dynamet's new CermeTi® particulate-reinforced titanium metal-matrix composites, which offer enhanced wear-resistance and modulus, will be evaluated and included in track designs.

Table IV. Thermomechanical Treatments and Ballistic Properties of Ti-6Al-4V

Roll Direction	Roll Temp. (°C)	Anneal Schedule	Thickness (mm)	20 mm FSP V_{50} (m/s)	.50 cal AP V_{50} (m/s)
Straight	954	788°C, 30 min AC	25.3	957	700
Cross	954	788°C, 30 min AC	25.5	978	698
Cross	954	1038°C, 30 min, AC	25.6	775	657
Cross	954	1038°C, 30 min, AC 788°C, 30 min, AC	25.6	741	644
Cross	954	None	25.6	984	700
Cross	1066	788°C, 30 min, AC	25.3	734	667
Straight	1066	788°C, 30 min, AC	25.3	757	675
Straight	1066	1038°C, 30 min, AC	25.3	756	663
Straight	1066	1038°C, 30 min, AC 788°C, 30 min, AC	25.2	734	650
Straight	1066	None	25.2	765	673
Straight	1066	927°C, 30 min, WQ 538°C, 6 hr, AC	25.4	784	645

AC = air cooled, WQ = water quenched

Some Army titanium components require so much machining that a powder-metallurgy approach makes sense. In that vein, a process that produces low-cost titanium-alloy powder would be quite advantageous. ADMA Products, of Twinsburg, Ohio, is completing a Phase I Army SBIR on low cost titanium components for armor and structural applications (via P/M processing). The company's thermohydrogen process (THP) has proven viable for producing low-cost titanium-alloy powders from a variety of generic sources that are then consolidated into useful, lower-cost titanium components. Plates of THP material will be ballistically tested by the Army Research Laboratory. In Phase II, processing and consolidation options to produce prototype components for army material will be optimized and scaled up. The candidate components are the Crusader recuperator sleeve, Crusader recoil tube sleeve, and the Bradley fighting vehicle commander's hatch.

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References

1. J.S. Montgomery et al., "Low-Cost Titanium Armors for Combat Vehicles," *JOM*, 49 (5) (1997), pp. 45–47.
2. Department of Defense, *Military Standard: V_{50} Ballistic Test for Armor*, MIL-STD-662E (1987).
3. W.A. Gooch et al., "Ballistic Performance of Titanium Against Laboratory Penetrators with Aspect Ratios of Ten or Greater," *Proc. 15th Int. Symp. Ballistics* (Medicine Hat, Alb., Canada: Nat'l. Defence Rsch. Establ., 1995).
4. W.A. Gooch et al., *Ballistic Penetration of Titanium Alloy Ti-6Al-4V, in Proceedings of the Lightweight Armor Systems Symposium '95* (Shrivenham, U.K.: The Royal Military College of Science, June 1995).
5. W.A. Gooch, M.S. Burkins, and K. Frank, "Ballistic Performance of Titanium Against Laboratory Penetrators," in *Pro.1st Australian Congress on Applied Mechanics '96* (Melbourne, Australia: Inst. of Engineers, February 1996).
6. M.S. Burkins, J.I. Paige, and J.S. Hansen, *A Ballistic Evaluation of Ti-6Al-4V vs. Long Rod Penetrators*, Army Research Laboratory Technical Report ARL-TR-1146 (Aberdeen Proving Ground, MD: U.S. Army Research Laboratory, July 1996).
7. M.G.H. Wells et al., "Evaluation of an Electron Beam Single Melt of Ti-6Al-4V Plate and Ballistic Property-Texture Relationships," *Titanium Workshop Proceedings*, ed. W.A. Gooch (Aberdeen Proving Ground, MD: U.S. Army Research Laboratory, February 2000).
8. M.S. Burkins and W.W. Love, "Effect of Annealing Temperature on the Ballistic Limit Velocity of Ti-6Al-4V ELI," *Proc. 16th Int. Symp. Ballistics* (Medicine Hat, Alb, Canada: Nat'l Defence Rsch. Establ. September 1996).
9. M.S. Burkins, W.W. Love, and J.R. Wood, *Effect of Annealing Temperature on the Ballistic Limit Velocity of Ti-6Al-4V ELI*, ARL-MR-359 (Aberdeen Proving Ground, MD: U.S. Army Research Laboratory, August 1997).
10. M.S. Burkins et al., *The Effect of Thermomechanical Processing on the Ballistic Limit Velocity of Extra Low Insterstitial Titanium Alloy Ti-6Al-4V*, ARL-MR-486 (Aberdeen Proving Ground, MD: U.S. Army Research Laboratory, July 2000).
11. M.G.H. Wells, D.J. Snoha, and M.E. Wells, *An Evaluation of Former Soviet Union Welding Processes on Commercially Pure Titanium*, U.S. Army Research Laboratory Technical Report, in process.

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