Low-Cost Titanium Armors for Combat Vehicles

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The U.S. Army has been using more and more titanium to either increase armor or reduce the weight of current combat vehicles. Future plans call for the development of combat vehicles that are 30 percent lighter. To achieve this target, the future-vehicle hull and turret will have to be manufactured using more ballistically efficient materials than rolled homogeneous steel armor. Low-cost titanium, with its good mechanical, ballistic, and corrosion properties and acceptable fabricability, offers the overall best alternative to achieving this objective.

INTRODUCTION

In response to ever-increasing anti-armor threats, ground combat vehicle weight has increased by 15–20 percent over the past decade as increased armor protection is required. For example, the M1 Abrams main battle tank has increased in weight from 54 tonnes to nearly 64 tonnes, and if this trend continues, the vehicle weight may increase by 2000 to a level that will drastically affect transportability, portable-bridge-crossing capability, and maneuverability. In response to this, the U.S. Army Tank-Automotive Command (TACOM) is evaluating alternative lighter weight materials such as titanium alloys and hybrid ceramic tile/polymer-matrix composites (PMCs), which are currently the only practical possibilities for lighter-weight structural armor applications.

Titanium alloys offer many advantages. The alloys have a high mass efficiency compared with rolled homogeneous (steel) armor (RHA) and aluminum alloys across a broad spectrum of ballistic threats as well as good multihit ballistic capability. No additional appliqué armor is necessary. They have a high strength-to-weight ratio and excellent corrosion resistance, which results in lower maintenance costs. Titanium alloys are readily fabricated in existing production facilities and are easily recycled; scrap and mill revert is currently remelted on a large-scale commercial basis.

Still, the alloys do have disadvantages. Specifically, a spall liner is required, and there are relatively high initial plate and fabrication (machining and welding) costs as compared with RHA.

Although PMCs offer some advantages (e.g., freedom from spalling against chemical threats, a quieter operator environment, and a high mass efficiency against ball and fragment ballistic threats), they have a number of disadvantages. There is a high cost for fabricated components compared with RHA or titanium, and PMCs are not readily fabricated in existing production facilities. Battlefield damage assessment (nondestructive testing) capability is not as well advanced, and multihit ballistic capability and automotive load-bearing capacity may be jeopardized due to structural changes after an initial ballistic strike. In addition, there is a fire and fume hazard to the vehicle interior. Finally, commercial manufacturing and recycling procedures are not fully established. Thus, while titanium alloys and PMCs both offer designers a means to reduce weight, titanium alloys are much more cost effective, and commercial manufacturing procedures are more fully developed.

During the past several years, titanium usage in combat vehicles has increased, and the trend is expected to continue. There is a continuing urgent need to reduce the weight of all ground vehicles and particularly the M1 Abrams main battle tank (Table I). The current steel turret, hull, and suspension represent 70% of the weight of the M1, but only 23% of its cost. Thus, a lighter-weight, higher-cost armor material would have a small impact on the cost of the finished product. Because of their unique combination of properties, titanium alloys offer the most cost-competitive way of substantially reducing weight while maintaining survivability. Table II shows some mechanical and ballistic properties of Ti-6Al-4V compared with RHA and aluminum alloy 5083. 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.

Titanium is routinely fabricated by conventional cutting, welding, and machining operations. Titanium may be readily cut with oxy-fuel cutting methods, and, in fact, cuts faster than steel. After plate cutting, the edges must be prepared for welding; the degree of edge preparation necessary for a good joint is presently being evaluated. Both major U.S. Army vehicle constructors (General Dynamics Land Systems [GDLS] and United Defense Limited Partnership [UDLP]) have undertaken extensive

Table I. The Increasing Weight of Abrams Main Battle Tank[1]

Year	Vehicle	Weight (tonnes)
1980	M1	54.4
1984	M1IP	55.3
1988	M1A1	58.9
1990	M1A2	62.1

welding development programs. Titanium can be welded using the equipment presently used with minor modifications and additional welder training.

Joints can be welded either autogenously or with a filler metal. The use of a matching filler metal (i.e., Ti-6Al-4V) is often employed to attain joints with improved ductility and toughness. But because titanium is very reactive to atmospheric gases above about 400°C, additional precautions must be taken to protect the weld metal and adjacent baseplate heat-affected zone until sufficient cooling has occurred. Argon or a mixture of helium and argon weld-shielding gas is required to protect the weld area from the atmosphere during and immediately after welding wherever the temperature exceeds about 400°C. For Army combat vehicle production, welding will likely occur outside an inert gas chamber, thereby necessitating use of primary, trailing, and backside gas shielding.

The machinability of titanium is similar to that of austenitic stainless steels. Titanium should be machined at lower speeds and higher feeds than those used for armor steels; however, a better surface finish is easier to achieve. Compared with armor steels, there are no significantly more difficult machining operations for titanium other than drilling and tapping.

TITANIUM ARMOR HISTORY

In general, the armor alloy with the best ballistic properties is the one that is the hardest, yet does not exhibit brittleness. When titanium armor (MIL-A-46077) was being developed in the late 1950s, it was difficult to keep test plates from cracking under ballistic attack. It was found that the interstitials carbon, hydrogen, oxygen, and nitrogen had an additive effect on brittle behavior. In fact, interstitial levels were so high that carbides, hydrides, oxides, and nitrides precipitated out. The presence of precipitates makes wet chemical analysis much more difficult, leading to some questions as to the real chemistries of the developmental alloys. In response to this, an extra-low interstitial (ELI) grade of Ti-6Al-4V in the mill-annealed condition was specified. Evidently, this was the only way the authors of the specification could be sure that the armor would behave in a ductile manner under ballistic attack.

During the 40 years since the original specification was promulgated, there have been dramatic improvements in the control of interstitials. It is now easier to hold carbon, hydrogen, and nitrogen to low levels. Oxygen has been and will always be difficult to control to low levels because of its presence in the ore and in the atmosphere, and it will react with titanium during thermomechanical treatment. Also, it is used as a strengthening agent in CP alloys, so it is present in scrap. Since the effects of interstitials on ballistic properties are additive, the level of oxygen can be relaxed somewhat, reducing cost if the other interstitials are held low. This will greatly impact cost, allowing the usage of lower-grade sponge or a higher fraction of scrap.

MIL-A-46077 has been Ti-6Al-4V ELI since its inception. Recent work on Ti-6Al-4V with relaxed interstitial requirements (purchased to MIL-T-9046J) has shown that lower-cost material can have the same ballistic properties. Since substitution by titanium can reduce the weight of combat vehicles, there was a need to develop an armor specification that includes low-cost titanium. A revised version of MIL-A-46077 has been drafted by the U.S. Army Research Laboratory (ARL) and should be published within the year. The revised specification now has four classes of armor: a Ti-6Al-4V ELI class (for continuity), two Ti-6Al-4V classes with relaxed interstitial requirements, and an "alternate composition" class. All classes have the same ballistic requirements. Ballistic testing of low-cost titanium by the ARL[2] has shown a dependence of resistance to penetration as a function of annealing temperature. It was found that optimum ballistic properties for the alloy tested were achieved with a 900°C anneal.

Table II. Some Properties of Steel, Aluminum, and Titanium Armor

	RHA MIL-A-12560	Aluminum 5083 MIL-A-46026	Ti-6Al-4V MIL-A-46077
Tensile Strength (MPa)	1,170	350	970
Density (g/cm³)	7.86	2.70	4.50
Specific Strength* (MPa-cm³/g)	150	130	220
Mass Efficiency (E_m)†	1 (by definition)	1.0–1.2	1.5

* Specific strength—tensile strength divided by density.

† Mass Efficiency (E_m)—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.

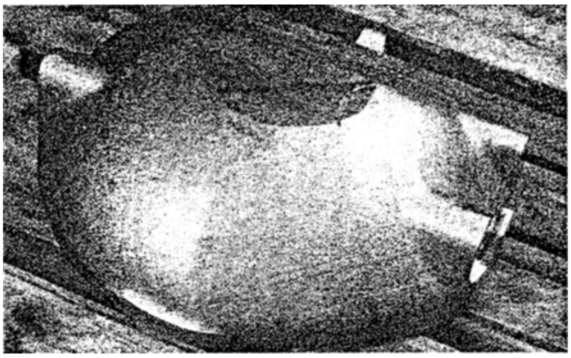

Figure 1. A forged and machined Ti-6Al-4V commander's hatch.[6]

MILITARY APPLICATIONS OF TITANIUM

Titanium's higher strength-to-weight ratio coupled with good corrosion resistance and excellent ballistic protection offers appreciable weight reduction over the conventional steel and aluminum alloys. Lower-cost titanium has spurred interest in the army and throughout the U.S. Department of Defense. For the army, this reduction in cost has justified a number of applications. The commander's hatch[7] in the M2 Bradley infantry fighting vehicle (originally made from forged aluminum) has been replaced with forged titanium at a weight savings of 35% and with greatly increased ballistic protection. This hatch (Figure 1) is made to the MIL-T-9046J specification with a Ti-6Al-4V composition. While this purchase specification has no ballistic requirements, it has a somewhat relaxed oxygen requirement (0.20 max instead of 0.14 max). It was used because it has ballistic properties equivalent to ELI material, but is less expensive. Thus, the Bradley commander's hatch can be said to be the first army application of low-cost titanium.

Appliqué armor is armor that is not used in a load-bearing application (i.e., it is bolted, glued, or somehow attached to a load-bearing frame). Since welding is not an issue, it allows easier incorporation into combat vehicles. The armored gun system, developed and promoted by UDLP, used titanium appliqué armor. Also, an armor upgrade for the Bradley includes wrought titanium plates as appliqué armor in selective areas for protection against larger ballistic threats. An up-armored, stretched version of the M113 armored personnel carrier also uses titanium appliqué armor. Any decision to up-armor these vehicles is greatly dependent on the installed cost.

TACOM is also using titanium to up-armor the M1 Abrams main battle tank. TACOM has evaluated a number of components on the M1 that are currently made from RHA for replacement with titanium. In Phase I of the program, two sets of seven components were produced—turret blow-off panels; a nuclear, biological, and chemical countermeasure system cover; a gunners primary sight cover; the engine top deck; a turret-pivot rack; the commander's hatch; and the commander's independent thermal viewer cap (Figure 2). Replacing all of these components results in a weight savings of 420 kg.

In Phase II, the blow-off panels and gunners primary sight cover were selected for upscaling; these have now been contracted to GDLS for manufacturing. The prototype hardware for these two components has been successfully tested and is part of the M1A2 upgrade program that began in October 1996 for a total of 580 vehicles over the next five years. Plans are to include the other components in the upgrade as more data become available on the manufacturing cost. TACOM and GDLS have also begun to look into replacing components made of cast homogeneous steel armor (MIL-A-11356) such as the turret ring with cast titanium.[1]

A 1996 manufacturing science and technology program addressed the low-cost, high-deposition-rate, out-of-chamber welding of titanium plates. In a parallel program, both GDLS and UDLP employed advanced welding processes for thick titanium plates to construct an armor package. The U.S. Army Tank Automotive Research, Development and Engineering Center furnished the titanium plates and ballistically tested the welded target. These programs are designed to determine if production welding techniques will yield weldment properties sufficient for ballistic structural armor applications. A prototype titanium turret was subsequently planned. Such a turret would reduce the weight of the M1 by four tonnes over the current steel counterpart.

There are plans to address other components on the M1 such as torsion bars. High-strength beta titanium alloys exhibit excellent fatigue properties and are good candidates for torsion bar applications. Additionally, TARDEC is investigating a titanium tow bar for the M1 vehicle through the Small Business Innovative Research program.

THE TITANIUM MARKET

Following the break-up of the Soviet Union, demands for aerospace-grade titanium used in the defense and commercial aviation industry decreased considerably in the early 1990s. In addition, the former Soviet Union offered titanium sponge to the world market at drastically reduced prices. These events left the U.S. titanium producers operating at well below capacity, and in fact, in 1992, RMI closed their sponge plant, leaving only two U.S. sponge producers—Timet and Oremet. More recently, the former Soviet Union has increased sponge prices and is now much more interested in exporting more mill products with an increased amount of value added. Additionally, the market for titanium in golf clubs has exploded in the past 18 months or so, and in 1996, amounted to some 4,500 tonnes.[3] The use of titanium in other recreational equipment has also been rapidly increasing. The result is that titanium is being thought of more as an engineering material with highly desirable properties at reasonable cost.

There are many approaches to reducing the cost of titanium, all of which are currently being explored.[4] Different methods of extracting the metal from ore, greater use of scrap, hearth melting and single hearth melting, and the reduction of surface preparation between ingot and slab and between slab and plate are all being examined. Additionally, relaxing quality-control requirements (e.g., ultrasonic inspection) and fabrication-procedure requirements (e.g., weld joint preparation) can also reduce cost without impairing serviceability for non-aerospace applications. Another potential cost reduction is in alloy formulation. The substitution of the more expensive vanadium with iron in Ti-6Al-4V has resulted in Timet's new alloy Timetal® 62S[5,6] Ti-6Al-1.8Fe-0.1Si. Finally, titanium plate is typically produced in specialty-steel rolling mills, and cost reductions can be obtained by an increase in product volume.

Most future vehicles have weight problems. To solve the weight issue, many steel components are being evaluated for substitution with titanium. For example, the U.S. Marines are looking at various options to reduce weight on the advanced amphibious assault vehicle. One of the options is lightweight armor. Another option is to reevaluate steel components such as road arms, support arms, road wheels, and gear housing for substitution with titanium.

There is also potential use of titanium alloys in future artillery systems. Crusader, the future self-propelled 155 mm howitzer, has many areas where titanium can be used. The army is presently evaluating two British designs of towed, 155 mm, lightweight howitzers, both of which employ a considerable quantity of Ti-6Al-4V. Titanium is used primarily in the trails and carriage, but also in the welded recoil units where it must withstand significant hydraulic pressure.

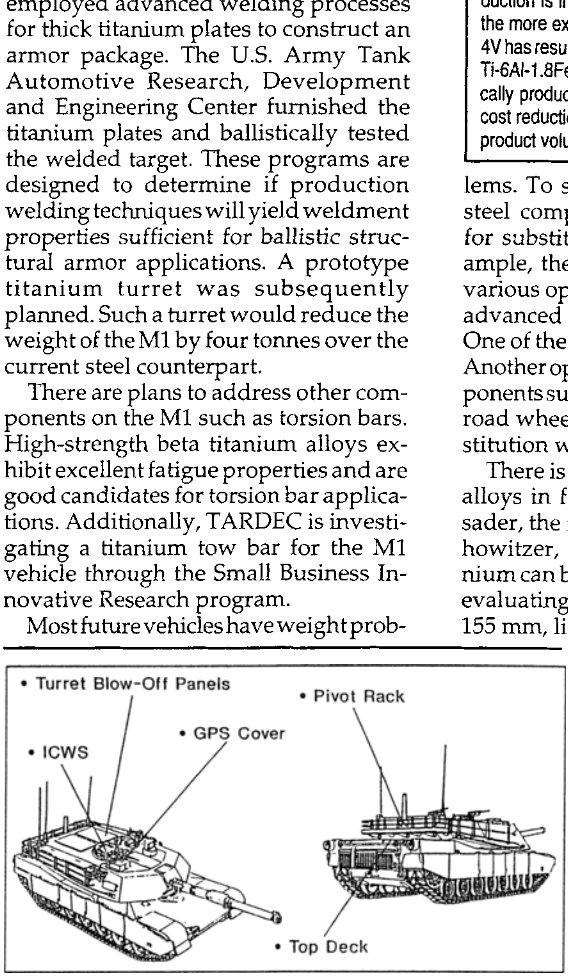

Figure 2. A M1 Abrams main battle tank component replacement.

Low-cost titanium has the potential to open up tri-service applications. The U.S. Navy is experiencing seawater pipe deterioration in heat exchangers on board its vessels. About 97 km of 90/10 copper-nickel pipes are replaced annually due to corrosion. Titanium offers better corrosion resistance as well as weight savings. Substitution with titanium will allow the navy to realize enormous maintenance cost savings by extending the service life and reducing refit costs.

The U.S. Air Force has also shown great interest in low-cost titanium. Cost reductions in the aerospace-grade titanium can be effected through the use of the cold-hearth melting process. This process can eliminate the need for double-arc melting. At the same time, rectangular cross-section ingots can be produced, thereby, eliminating the need for the initial thermomechanical steps that are necessary in order to square up the round ingots produced by vacuum arc remelting.

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