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Suppression of Material Failure Modes in Titanium Armors

by William J. Bruchey

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14. ABSTRACT

Previous research by the U.S. Army Research Laboratory (ARL) has shown that the most common titanium alloy, Ti-6Al-4V, provides weight-effective protection against small-arms projectiles. In armor applications, titanium is susceptible to adiabatic shear and spall failure at the back surface. The large spall plugs that form can be a significant factor in behind-armor vulnerability and lethality. As the U.S. Army moves towards lighter and lighter Future Combat Systems class vehicles, thinner and lighter armors and structural elements will be needed. Particularly, the rear structural element in an armor must provide protection producing minimal behind-armor debris.
ARL, in cooperation with the PM-Combat Systems, has undertaken a program to address this problem. Two-layer titanium composites were investigated. The initial or impact facing layer consisted of Ti-6Al-4V, with a backing layer of a nonplugging/spalling material. Backing layers consisted of commercially pure titanium, rolled homogeneous armor, steel, or aluminum. For each material combination, the two layers were either metallurgically bonded using explosive welding or diffusion bonded using hot isostatic pressing.

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1. Introduction

As early as 1950, Pitler and Hurlich[1] noted that titanium alloys showed promise as armors against small arms projectiles. By the early 1960s, Sliney[2] presented ballistic performance data for the Ti-6Al-4V alloy that demonstrated significant weight reductions over steel armors for a variety of small arms threats. Little follow-on work with larger threats was conducted due to the prohibitive cost of the titanium.

Recently, the U.S. Army Tank-Automotive Research, Development, and Engineering Center, Warren, MI, funded the Weapons and Materials Research Directorate of the U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, to complete a ballistic evaluation of thick titanium plates with tungsten alloy and depleted uranium penetrators.[3] The U.S. Department of Interior Bureau of Mines at Albany, OR, was funded to purchase 76.2- to 101.6-mm-thick Ti-6Al-4V plates manufactured to the common MIL-T-9046J[4] specification.

2. Background

In the work of Burkins et al.[3], the adiabatic shear and spalling behavior of the Ti-6Al-4V alloy were noted. The consequence of this behavior can be seen in figure 1, which shows how the ballistic behavior is effected by the free back surface of a Ti-6Al-4V armor plate. Due to the adiabatic shear and spall failure of the back face of titanium armor targets, an ~5%–10% greater thickness of titanium alloy can be perforated at the same velocity as compared to semi-infinite titanium alloy.

Figure 2 shows an example of the severe back surface spalling that can occur in high-strength titanium alloys. Fragments resulting from this ballistic event would increase system vulnerability and result in damage to personnel and equipment behind the armor. This is a concern should titanium alloy be used as a rear structural material for armored vehicles. The intention of this study was to alleviate these problems and produce a titanium structural material that was suitable for the inner structural element of a combat vehicle. The approach taken was to

[1]Pitler, R.; Hurlich, A. *Some Mechanical and Ballistic Properties of Titanium and Titanium Alloys*; 401/17; Watertown Arsenal Laboratory: Watertown, MA, March 1950 (ADA 951655).

[2]Sliney, J. *Status and Potential of Titanium Armor; Proceedings of the Metallurgical Advisory Committee on Rolled Armor*; AMRA MS 64-04; U.S. Army Materials Research Agency: Watertown, MA, January 1964 (AD 354853).

[3]Burkins, M.; Paige, J.; Hansen, J. *A Ballistic Evaluation of Ti-6A1-4V vs. Long Rod Penetrators*; ARL-TR-1146; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, July 1996.

[4]MIL-T-9046J. *Military Specifications—Titanium and Titanium Alloy (Sheet-Strip-Plate)* **1993**.

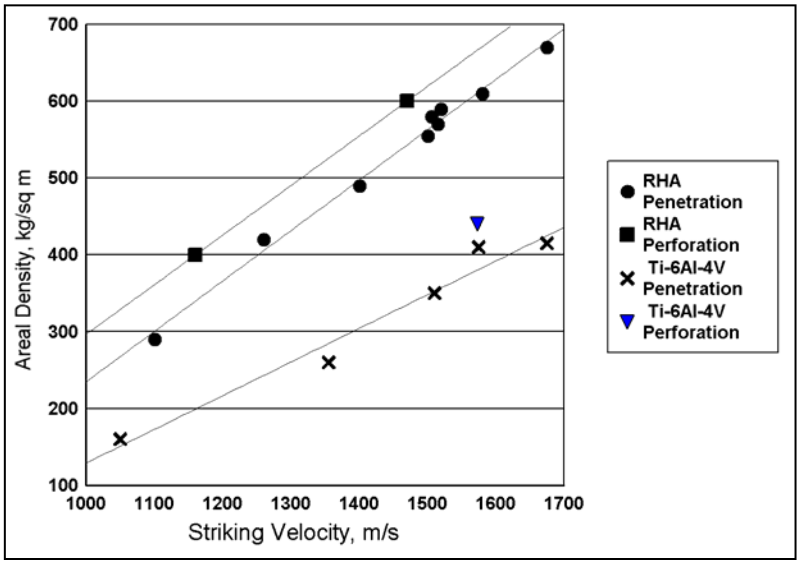

Figure 1. Comparison of penetration and perforation behavior of rolled homogeneous armor (RHA) and Ti-6Al-4V armor materials.

Figure 2. Severe spall of unconfined back surface due to ballistic impact on finite thickness titanium armor plate.

develop metallic laminates composed of titanium alloy plates with a backing plate of a dissimilar material to suppress the adiabatic shear failure and back face spalling.

3. Materials and Processing

The Ti-6Al-4V material used in all phases of the program was purchased to the military specification, MIL-T-9046J. Chemistries and typical properties can be found in Burkins et al.[3] The monolithic titanium alloy armor thickness was fixed at 38.1 mm. In the laminate armor tests, the thickness of the Ti-6Al-4V front plate was fixed at 31.75 mm and the rear plate at 6.35 mm for the same total thickness of 38.1 mm. All the plates had 304.8- × 304.8-mm lateral dimensions.

Three different backing plate materials were chosen for the bimetallic laminates: aluminum (1100), RHA steel, and commercially pure titanium (C.P.). These material combinations provided a wide range of strengths, toughnesses, densities, and metallurgical compatibilities with the Ti-6Al-4V armor front plate. Two methods were chosen for fabrication of the laminates: explosive welding and hot isostatic pressing (HIP).

Explosive welding is a solid state welding process, which uses controlled explosive detonations to force two or more metals together at high velocities (figure 3). It has the advantage of effectively scrubbing clean both metal surfaces during the joining process. Because the time durations are so short, the reaction zones are extremely small with a correspondingly small heat effected zone. Because the base metals remain at near ambient temperatures, the formation of

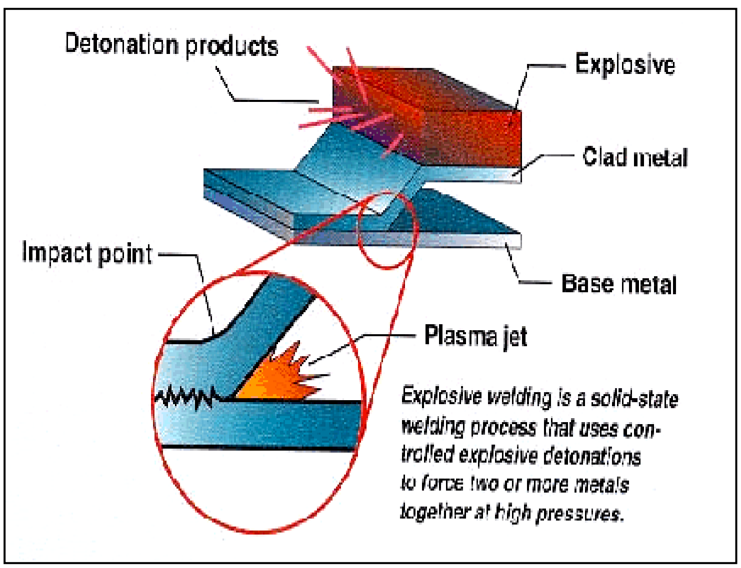

Figure 3. Schematic of explosive welding process.

brittle intermetallics is suppressed. This technique was used to join all the combinations of materials used in the bimetallic laminates.

HIP, figure 4, was chosen as an alternative to explosive bonding for joining the titanium alloy to the commercially pure titanium due to the compatibility of the two materials. HIPing is a solid state diffusion process carried out at high temperature and pressure. To join the titanium alloy and C.P. titanium, the materials were processed in the HIP press for 2 hr at 900 °C and 15-ksi pressure. HIP bonding offers the advantage of no explosives, and there is an industrial capability to produce parts in sizes suitable for combat vehicles.

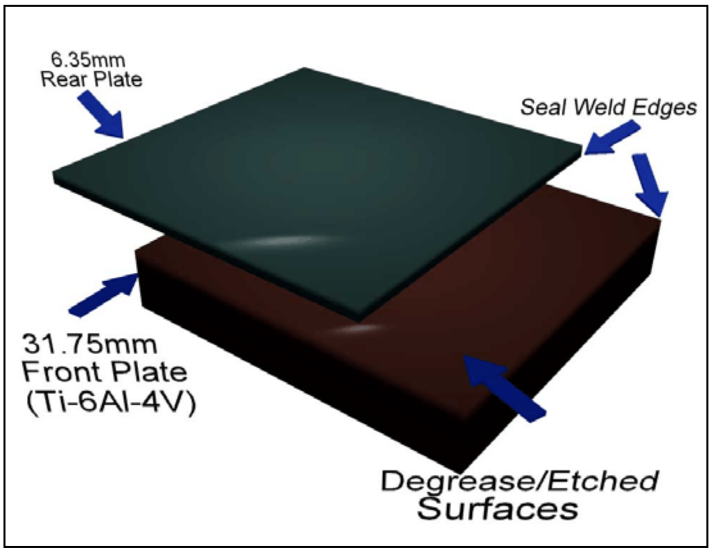

Figure 4. Sketch of 20-mm fragment simulating projectile (FSP).

4. Test Methodology

Ballistic limit velocities were determined at 0° obliquity to the target surface. Limit velocity perforation testing involves varying the impact velocity against a single thickness of plate and determining the minimum velocity necessary for perforation. The limit velocity (V_L) is defined as the critical velocity at which the target is just perforated (i.e., the residual velocity is zero). The V_L was calculated averaging the highest partial and lowest complete penetration velocity.

The penetrator chosen for the evaluation was the standard 20-mm FSP shown in figure 5. This projectile was selected because the geometry of the nose tends to emphasize the spalling and plugging behavior of the materials.

The penetrators were fired from a laboratory gun consisting of a 37-mm breech assembly with a 26-mm smoothbore barrel. A custom-built polypropylene sabot system was used to launch the

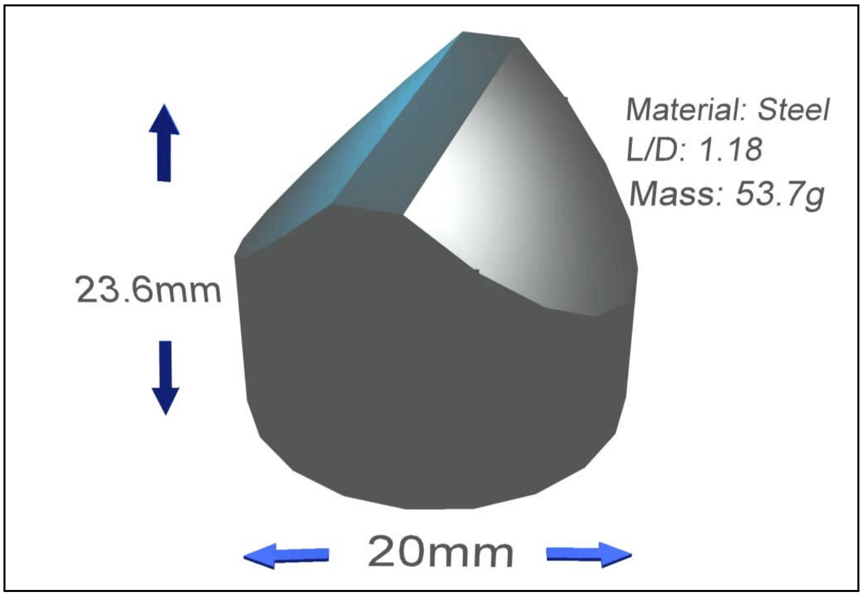

Figure 5. Comparison of limit velocity performance of candidate titanium laminates vs. the weight equivalent monolithic titanium armor plate.

projectiles. The target was positioned 1.5 m downrange from the muzzle of the gun. The propellant weights were adjusted from shot-to-shot to achieve desired striking velocities.

For this test penetrator, the performance of the modified titanium plates was compared to the 0° obliquity baseline performance of monolithic Ti-6Al-4V armor of the same weight or areal density. Comparisons were based on the areal density of the candidate armor material needed to defeat the projectile at a given striking velocity. Areal density is defined as the thickness of material perforated (or depth penetrated) times the density of this material.

5. Results

A series of shots were fired into each laminate combination to obtain the ballistic limit velocity. Figure 6 shows the ballistic limit velocity, V_L, for each of the targets plotted as a function of their areal densities. Based on the data of Burkins et al.,[3] the solid diagonal line represents the V_L of solid titanium alloy as a function of plate thickness or areal density. For the laminate armor data points lying above the diagonal, performance exceeds that of the monolithic titanium plate. For data points below the diagonal, the performance of the laminates are inferior to the monolithic plate. Both joining techniques show that the combination of Ti-6Al-4V laminated to C.P. Ti performs better than the monolithic titanium alloy on a weight basis. Both the Al and RHA laminates show performance decrements on a weight basis. The combination of HIP pressing and a laminate of titanium alloy and C.P. titanium shows a 5%–10% improvement in

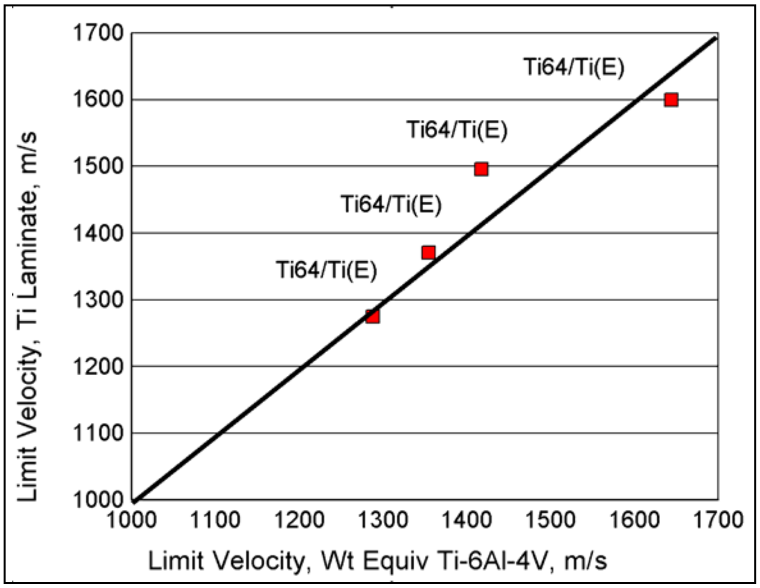

Figure 6. Comparison of limit velocity for titanium laminates and Ti-6A1-4V alloy.

the V_L. This improvement is the same magnitude as the loss in going from semi-infinite penetration to finite plate perforation shown in figure 1.

Each of the targets was sectioned through the penetration channel to observe the integrity of the bond between the front and back plate and the degree of spalling produced. Figure 7 shows the penetration channel for the best performer, the Ti-6Al-4V/C.P. Ti. Note the absence of a spall ring as compared to figure 2 and the absence of any delamination of the layers. Similar

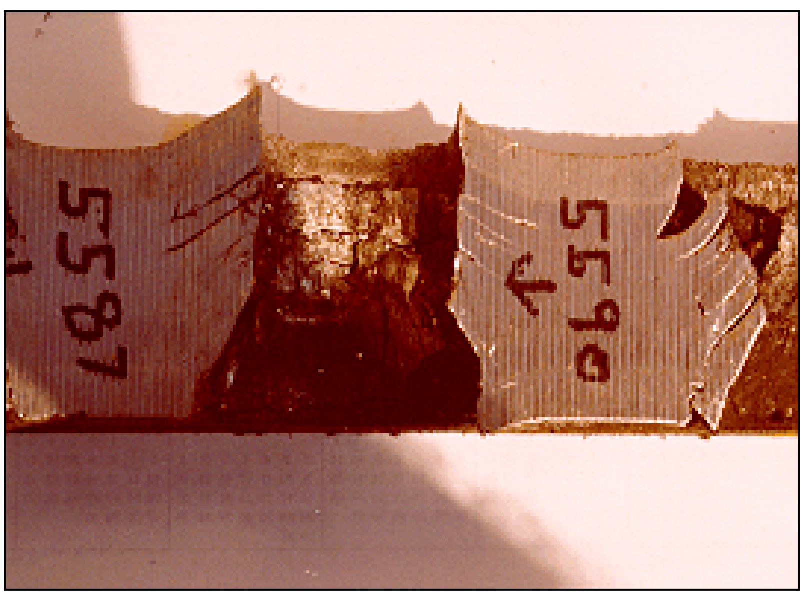

Figure 7. Typical penetration channel through HIP-bonded Ti-6Al-4V laminate. Penetration direction is top to bottom.

observations were made on each of the combinations of materials. Figure 8 shows the diameter of the spall ring for each bimetallic laminate material tested. Again, the HIP bonded laminate of titanium alloy and C.P. Ti was the best. The maximum diameter of the penetration channel was approximately the diameter of the original projectile, nearly eliminating secondary lethality effects from spall behind the armor.

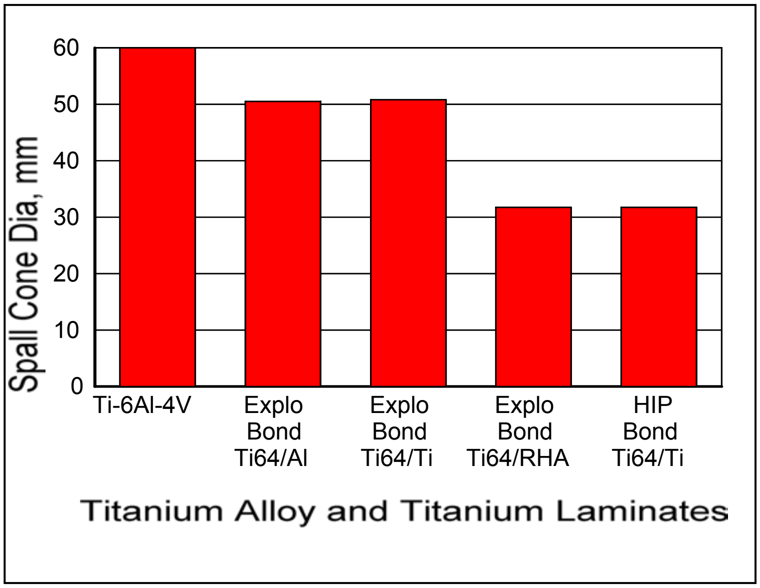

Figure 8. Spall cone diameters for titanium and titanium laminates impacted by 20-mm FSPs.

6. Conclusions

Laminated titanium armor designs offer enhanced performance of the baseline monolithic Ti-6Al-4V alloy and identifies the advantages of using these bimetallic laminates as rear structural elements of an armored vehicle. Two joining techniques were investigated. Of the two, HIP bonding of Ti-6Al-4V to C.P. Ti had the best combination of ballistic performance and spall suppression. HIP bonding is an existing commercially available process with the capability to bond sections large enough for combat vehicles.

Results to date address only one possible combination for the laminate: a biplate with fixed thicknesses of each component. Planned future efforts will examine different thickness ratios and multiple layer schemes.

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