

The Design and Application of Titanium Alloys to U.S. Army Platforms

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ABSTRACT

Titanium alloys have long been used for reducing system weight in airframe structure and jet engine components. The high cost of titanium, however, has historically prevented their application to military ground vehicles. In recent years, the cost of titanium has fallen relative to the cost of composite and ceramic armors and titanium is now a valid option for some Army applications, whether for weight reduction or improved ballistic performance. The distinct advantages of low density, high strength, a large competitive industrial base, and well established forming and shaping techniques establishes titanium as an excellent material for many military applications. The U.S. Army Research Laboratory (ARL) has invested significant research efforts in understanding the material processing requirements for ground versus aerospace applications and this paper will provide an overview of that research. A major concurrent effort has been amending existing military specifications to allow the use of lower cost, higher oxygen content titanium alloys that meet specific ground applications. The paper will end with a review of some of the current applications of titanium on US Army platforms and augments previous presentations given in this forum.

INTRODUCTION

Titanium alloys have long been used for reducing system weight in airframe structure and jet engine components. The high cost of titanium, however, has historically prevented the application to military ground vehicles. In recent years, the cost of titanium has fallen relative to the cost of composite and ceramic armors and titanium is now a valid option for some armor applications.

As early as 1950, Pitler and Hurlich [1] noted that titanium alloys showed promise as armors against small arms projectiles. By the early 1960's, Sliney [2] presented ballistic performance data for Ti-6Al-4V alloy that demonstrated significant weight reductions over steel armors for small arms threats. Little work with

larger threats was conducted due to the then prohibitive cost of the titanium. Since the early 1990's, ARL has undertaken a research effort to develop baseline titanium ballistic performance data against a range of penetrators and fragments. The publication of revised military specifications with new classes of titanium alloys, processed through lower-cost plasma and electron-beam melting technology has expanded the use of titanium for military applications

BACKGROUND

Titanium can exist in a hexagonal close-packed crystal structure (known as the alpha phase) and a body-centered cubic structure (known as the beta phase). In unalloyed titanium, the alpha phase is stable at all temperatures up to 882° C, where transformation to the beta phase occurs. This transformation temperature is known as the beta transus temperature. The beta phase is stable from 882° C to the melting point. As alloying elements are added to pure titanium, the phase transformation temperature and the amount of each phase change. Alloy additions to titanium, except tin and zirconium, tend to stabilize either the alpha or beta phase. Ti-6Al-4V, the most common titanium alloy, contains mixtures of alpha and beta phases and is therefore classified as an alpha-beta alloy. The aluminum is an alpha stabilizer, which stabilizes the alpha phase to higher temperatures, and the vanadium is a beta stabilizer, which stabilizes the beta phase to lower temperatures. The addition of these alloying elements raises the beta transus temperature to approximately 996° C. Alpha-beta alloys, such as Ti-6Al-4V, are of interest for armor applications because the alloys are generally weldable, can be heat treated, and offer moderate to high strength [3]. Ti-6Al-4V alloy can be ordered to a variety of commercial and military specifications. Extra Low Interstitial (ELI) grade plates, simultaneously conforming to MIL-T-9046J, AB-2 (aerospace) and MIL-A-46077G (armor) specifications are used in many applications. The specifications define alloy chemistry ranges, minimum mechanical properties, and, in the case

of MIL-A-46077G, ballistic requirements. Typical chemical compositions of titanium plate are listed in Table 1 for a Class 1 ELI alloy; mechanical property data for a typical MIL-T-9046J, AB-2 (aerospace) plate are found in Table 2. The hardness values are representative of the plates tested; hardness is not specified in MIL-T-9046J.

U.S. rolled homogeneous armor (RHA) steel is used as the baseline for most ballistic comparisons. RHA mechanical properties are also provided in Table 2 for plate thicknesses ranging from 38-mm to 152-mm; the mechanical properties of RHA vary as a function of plate

thickness due to differences in thermomechanical processing. A 38-mm RHA plate has higher strength and hardness than a 152-mm plate. Ti-6-4 Titanium has poor hardenability in thick sections and cannot be rapidly quenched. However, excellent mechanical properties can be developed into wrought plate through thermomechanical working (rolling). Titanium mechanical properties are very uniform across the plate thickness that increases the relative ballistic performance when compared to an equivalent thickness of RHA. In thick sections, titanium has significantly better mechanical properties for ballistic application than RHA.

Table 1. Typical Chemical Compositions for Class 1 Titanium Plates by Weight-Percent

Al	V	C	O	N	H	Fe	Ti
5.50-6.50	3.50-4.50	0.04 Max	0.14 Max	0.02 Max	0.0125 Max	0.25 Max	Balance

Table 2. Typical Titanium and RHA Mechanical Properties

MATERIAL	SOURCE	DENSITY g/cm ³	TENSILE STRENGTH	HARDNESS	ELONGATION %
Ti-6Al-4V	MIL-T-9046J	4.45	>896 MPa	302-364HB	>10
RHA	MIL-A-12560	7.85	794-951 MPa	241-331HB	11-21

TITANIUM MILITARY SPECIFICATION MIL-DTL-46077G

An important factor in the use of titanium alloys for military applications is Military Specification MIL-DTL-46077G that defines different classes of titanium that can be used as armor [4]. While commercial specifications such as SAE-AMS-T-9046, SAE-AMS4911 or ASTM-B265 maintain quality control through mechanical properties, chemistry and processing, MIL-DTL-46077G emphasizes ballistic response to maintain quality control; no process is specified. This specification covers the thickness ranges of 0.125”- 4.000” and was revised last on 28 September 2006. The main change from the previous specification is the expansion of the thickness range in thin sections down to 0.125”; the ballistic acceptance tables for this range have not been finalized to date and developing an acceptable ballistic test has proven difficult due to the thin cross-sections of the plate and necessity to discern quality variations due to processing.

The emphasis in recent amendments to the specification has been to incorporate new classes of titanium armor that utilize lower-cost titanium processing and alternate alloys. Table 3 provides the current four classes of titanium that can be specified under the MIL-DTL-46077G. While all four classes have the same strength and ballistic requirements, the direction has been to increase the oxygen content to a maximum of 0.30% that has allowed the use of lower-cost processing technologies such as Electron Beam or Plasma Melting for both Class 3 and 4. Armor grade titanium has a greater tolerance to oxygen content than other applications in the aerospace industry. Class 4 titanium, unlike Class 1-3, allows alternate alloys to be utilized for armor applications and has opened up new alloy designations that utilize different alloying elements; this can have additional impact on overall alloy cost by utilizing lower cost alloying elements.

Table 3. MIL-DTL-46077G Titanium Armor Specification

	Chemistry	Max. O ₂ Content	Comments
Class 1	6AL- 4V	0.14%	<i>ELI-</i> 10% Elongation Min.
Class 2	6AL- 4V	0.20%	<i>Common Armor</i> 6% Elongation Min.
Class 3	6AL- 4V	0.30%	<i>High Scrap Content</i> Weld & cold temp issues
Class 4	Not Limited	0.30%	<i>For future developments</i>

BALLISTIC RESPONSE OF TITANIUM TO FRAGMENTS AND PROJECTILES

ARL has conducted extensive analysis of the ballistic response of titanium to both projectiles and fragment simulators [5-12] and more details can be found in the references. As seen in Table 2, titanium has similar strength, hardness and elongation to ballistic steel, but the density is 43% less. This strength to density ratio is the primary factor in the greater performance of titanium over ballistic steel. Figure 1 illustrates the penetration of a Ti-6Al-V alpha-beta titanium and RHA steel by a long rod penetrator at velocities from 500 m/s up to 2600 m/s. The penetration into both metals is approximately equal up to about 1700 m/s and has a mass efficiency compared to steel of 1.87 at 1000 m/s dropping off to 1.44 at 2000 m/s when the densities are considered. Even

when the impact velocities approach the hydrodynamic limit where material strengths can be ignored, the penetration density law results in a theoretical performance of 1.3 times that of steel.

Microstructure and processing technology can still have a significant effect on the performance at Ordnance velocities. Figures 2 and 3 show two Ti-6Al-4V ELI plates that were beta- and alpha-beta-processed and then impacted by a 20mm fragment simulating projectile. The large difference noted in the ballistic performance between the plates tends to indicate that the failure mechanisms were in some way different. Observation of the rear plate surface failures for perforating and near-perforating impacts showed this to be the case. The beta processed plates failed by adiabatic shear plugging. This low-energy failure mode caused a titanium plug to be ejected

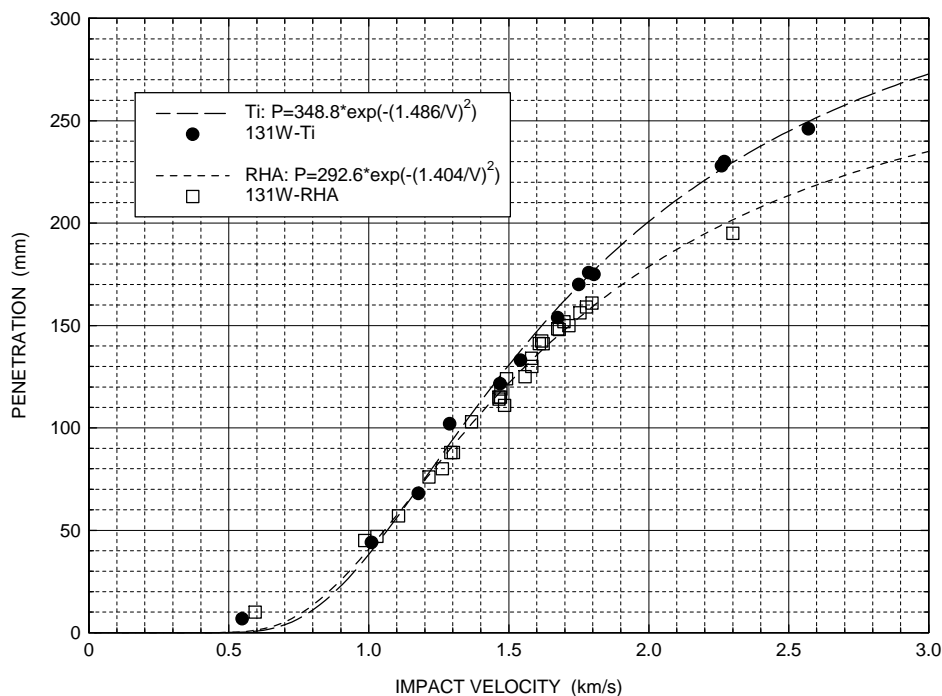


Figure 1. Penetration of a Tungsten Long Rod Penetrator into RHA and Titanium

from the rear surface of plate after the FSP penetrated approximately 6-mm into the plate and has been described in previous ARL work [12-14]. The plates that were alpha-beta processed failed by a mixed process of bulging, delamination, shearing, and spalling. However, this failure occurred only after the FSP had penetrated approximately 15-mm into the plate, requiring the FSP to penetrate significantly deeper into the armor than for the beta-processed plates. Rolling or annealing at temperatures above the beta transus significantly reduced the performance.

Adiabatic shear plugging is inherent in titanium as a result of shear-induced strain localizations and the low heat transfer properties of titanium. Figure 4 shows the deep penetration of a long rod tungsten penetrator into a titanium plate. The adiabatic shear bands in the sectioned plate are visible parallel to the penetration channel. The shear banding happens all

along the circular penetration channel and then the titanium fragments mix with the tungsten rod fragments. In a complete perforation of the plate, the adiabatic titanium chips and penetrator debris are ejected and the penetration cavity wall appears very smooth. When an eroded penetrator comes within approximately one penetrator diameter of the rear free surface, the plate will eject a shear plug that has a larger diameter than the penetrator. This spall plug is generally not penetrated during the interaction and decreases performance. Figure 5 shows a large spall plug induced in a four inch plate that resulted in an approximate 20% loss in penetrator/target interaction. For this reason, titanium is not recommended for standalone use and low density backings, such as aluminum or composites, increase performance as the spall plug is held in place and contribute to erosion of the penetrator.

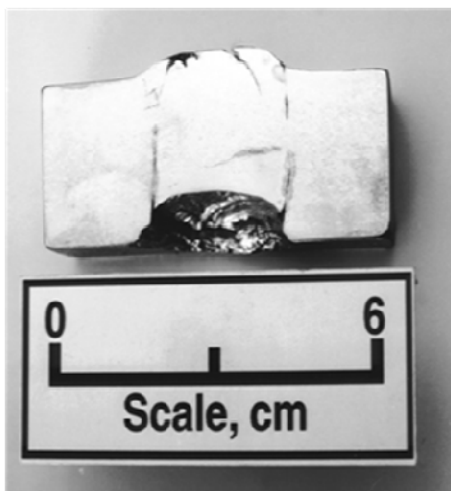


Figure 2. Cross-section of Impact Crater from 20-mm FSP for Beta Processed Plate

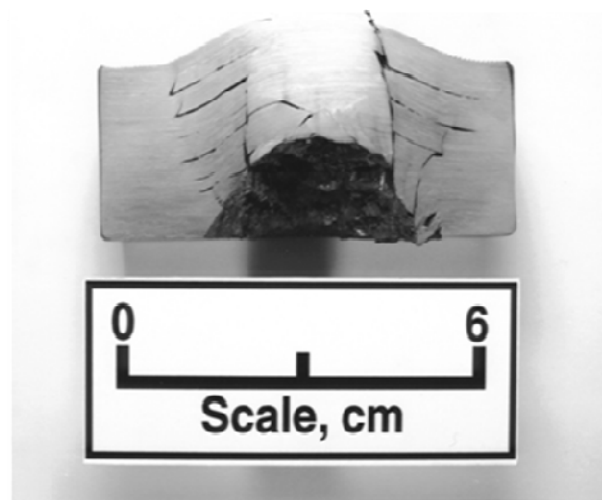


Figure 3. Cross-section of Impact Crater from 20-mm FSP for Alpha-Beta-Processed Plate

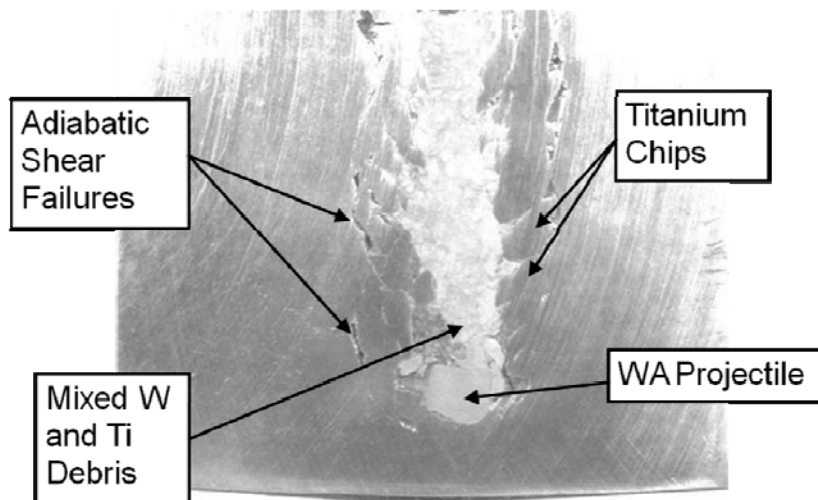


Figure 4. Deep Penetration of a Tungsten Long Rod Penetrator into Titanium showing Adiabatic Shear Bands

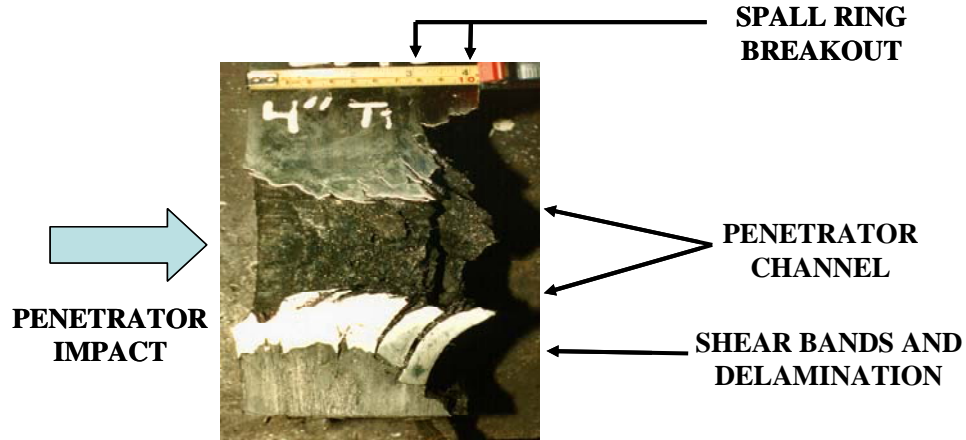


Figure 5. Spall Plug Breakout of a 100mm (4.0'') Titanium Plate after Perforation by a Long Rod Penetrator

EFFECT OF MECHANICAL PROPERTIES ON BALLISTIC PERFORMANCE

The quasi-static mechanical properties of titanium are very important for most engineering applications and were included in the property requirements in MIL-DTL-46077G for Class 1 and 2 titanium. However, for armor applications, the impact of varying the mechanical properties is not apparent and processing history is more important. The most complete analysis of these effects were conducted by Burkins, Love and Wood where a set of Ti-6Al-4V ELI plates were subjected to a series of annealing temperatures and the effects on the mechanical properties were determined [13]. The results

on the samples from the original single 28.5mm plate are summarized in Figure 6 where the effect of heat treating or working the plates over the beta transus temperature is obvious. The initial vacuum creep-flatten process produced ballistic plate with a performance similar to plates subjected to additional annealing below the beta transus. Plates annealed above the beta transus have a microstructure change to a Widmanstätten alpha-beta structure as seen in Figure 7. The effect on ballistic performance compared to transverse yield strength, transverse elongation and Charpy impact data are shown in Figures 8-10. The annealing step could be omitted to reduce cost or the anneal temperature could be increased to 900°C to obtain the highest performance.

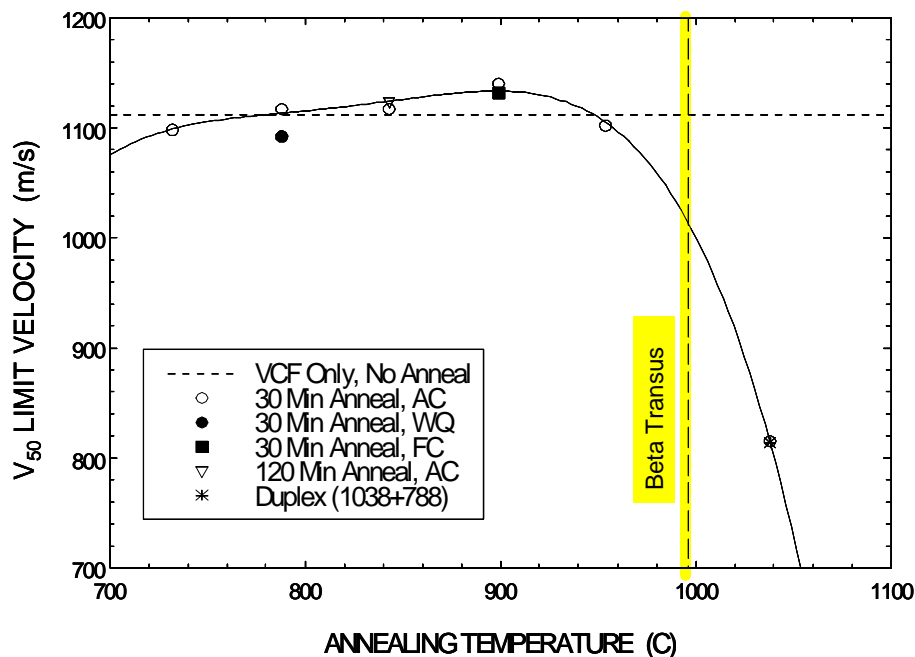


Figure 6. Effect of Annealing Temperature on Ballistic Performance

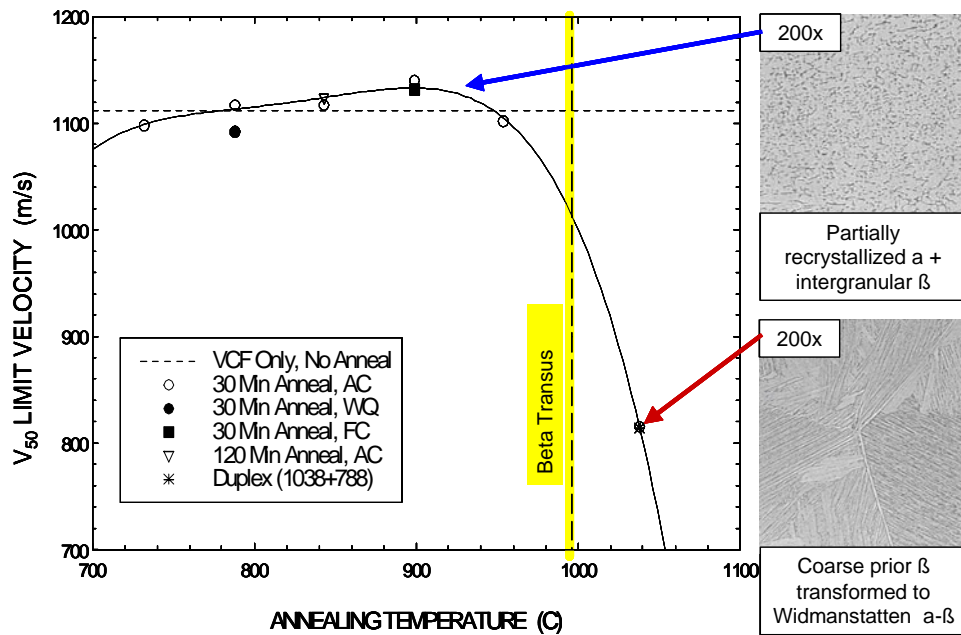


Figure 7. Change in Microstructure for Annealing over the Beta Transus Temperature

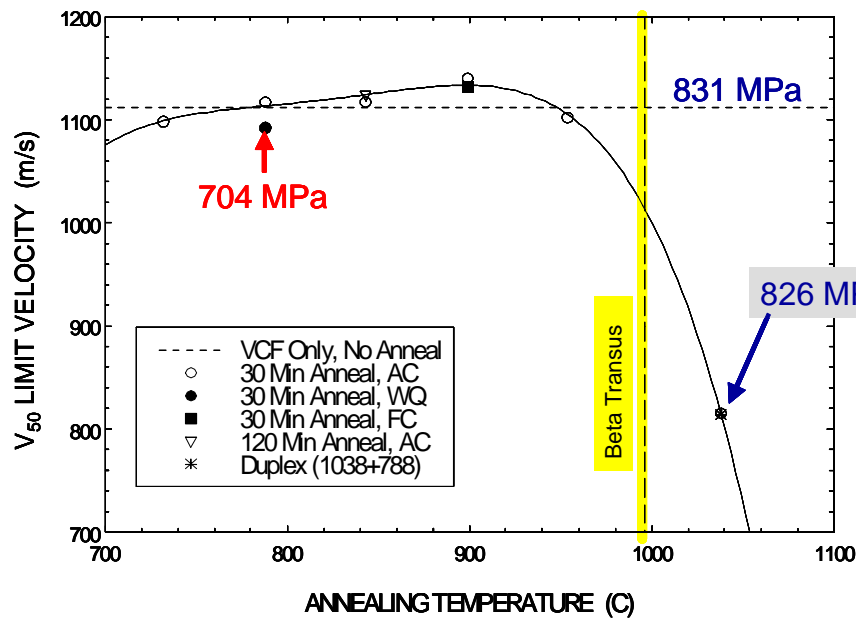


Figure 8. Change in Transverse Yield Strength with Annealing Temperature

EFFECT OF THERMOMECHANICAL PROCESSING ON BALLISTIC PERFORMANCE

In an effort to provide further data on processing of titanium armor plate, ARL and the U.S. Department of Energy Albany Research Center (ALRC) performed a joint research program to evaluate the effect of thermomechanical processing on the ballistic limit velocity of an ELI grade of Ti-6Al-4V [14-15]. ALRC

obtained MIL-T-9046J, AB-2 plates from RMI Titanium Company, rolled these plates to final thickness, performed the annealing, and collected mechanical and microstructural information. ARL then tested the plates with 20-mm fragment-simulating projectiles (FSPs) and 12.7-mm armor-piercing (AP) M2 bullets in order to determine the ballistic limit velocity of each plate. The ballistic limit velocities were then compared to assess the effect of changes in rolling and heat treatment.

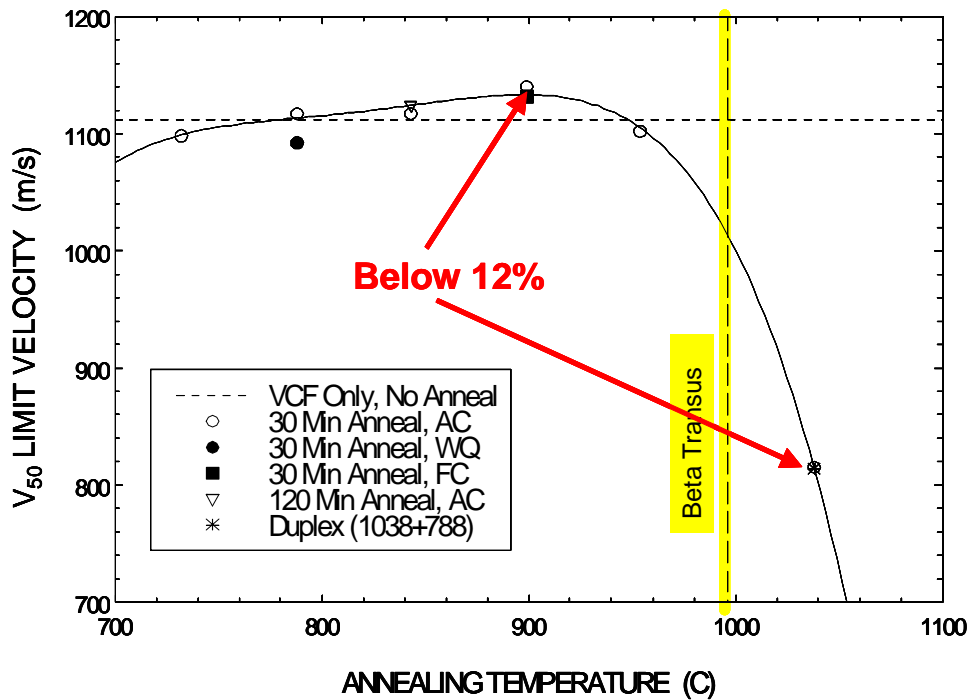


Figure 9. Effect of Transverse Elongation with Annealing Temperature

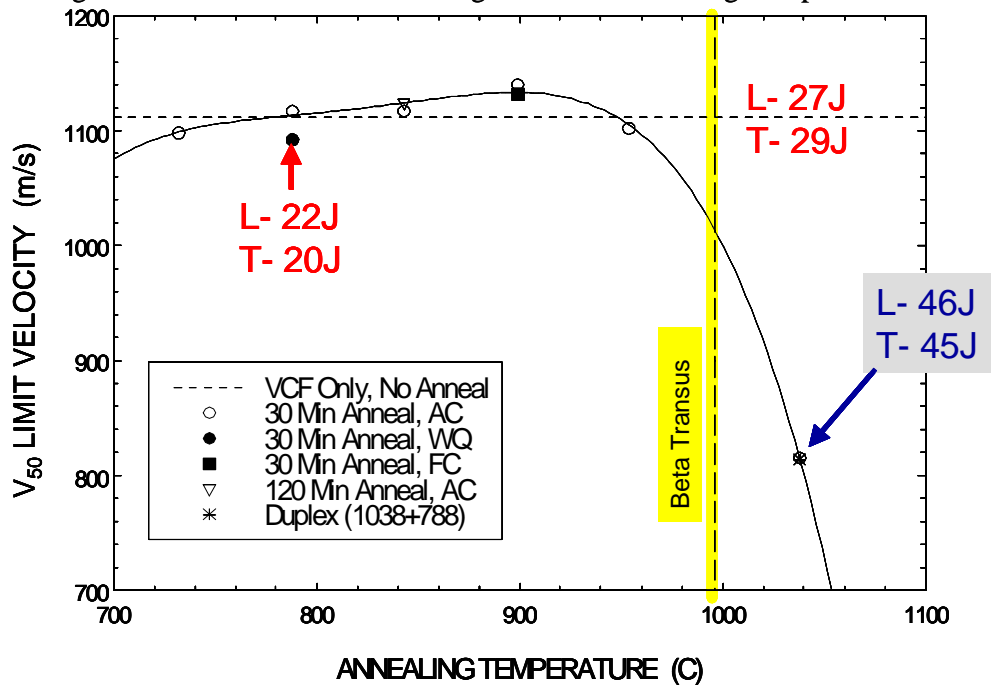


Figure 10. Effect on Charpy Impact Results with Annealing Temperature

The starting material was commercially produced 127-mm-thick Ti-6Al-4V ELI alloy plate product. Each plate was coated with a silica-based material to reduce oxygen contamination, placed into the furnace, and soaked for two hours at either 1,066° C (beta) or 954° C (alpha-

beta), and step forged to 108-mm first and then 89-mm. The step forging was done without reheating. Upon completion, the plates were returned to the furnace and reheated for 20 minutes. The plates were then, either unidirectionally (straight) rolled or cross-rolled at the

same temperature used in the forging operation (1,066° C or 954° C). The rolling schedule consisted of two passes at 12% reduction in thickness, two passes at 15% reduction in thickness, three passes at 20% reduction in thickness, and one final pass at the final mill setting of 25.4 mm. Each plate was reheated for 20 minutes after every second pass through the mill. Following the final pass, the plates were placed on a rack and air cooled to room temperature.

Four different annealing heat treatments were used at the completion of rolling and air cooling: (1) a beta anneal at 1,038° C for 30 minutes with an air cool (AC); (2) a beta plus alpha-beta anneal at 1,038° C for 30 minutes with an AC, followed by 788° C for 30 minutes with an AC; (3) an alpha-beta anneal at 788° C for 30 minutes with an AC; and (4) a solution treat and age (STA) at 927° C for 30 minutes with a water quench (WQ), followed by 538° C for 6 hours with an AC. As an experimental control, the final heat treatment was omitted for some of the plates. Following heat treatment, all the plates were sand-blasted to remove any remaining protective coating. All plates forged, rolled, or annealed in the beta region had a typical structure of plate-like alpha and intergranular beta with alpha at the prior beta grain boundaries. All plates forged, rolled, and annealed

in the alpha-beta region had a typical structure of equiaxed alpha grains and intergranular beta.

V₅₀ limit velocities were obtained for all eleven plate conditions, tested with both the 20-mm FSP and 12.7-mm APM2 projectiles. Figure 11 shows graphically the V₅₀ difference for the eleven plate conditions. The required V₅₀ values were derived from the acceptance tables in MIL-A-46077D. Regardless of the penetrator used, only three plates (S1, C1, and C4) passed the ballistic requirements of MIL-A-46077D, even though these three plates also failed to meet the elongation requirements of MIL-A-46077D. Beta-processed plates, either rolled or annealed at temperatures above the beta transus, had lower V₅₀ ballistic limit velocities for both the 20-mm FSP and the 12.7-mm APM2. The magnitude of the effect was much greater for the 20-mm FSP (~200 m/s) than for the APM2 (~40 m/s), confirming a trend that had been indicated in prior data [12]. The plates that received no additional anneal treatment (C4 and S5) gave a ballistic performance comparable to similarly processed plates that received an alpha-beta anneal treatment (C1 and S2). For the APM2 tests, cross rolling provided no significant difference in V₅₀ as compared to straight rolling (S1 vs. C1 and C5 vs. S2). For the 20-mm FSP tests, cross rolling seemed to provide a slightly

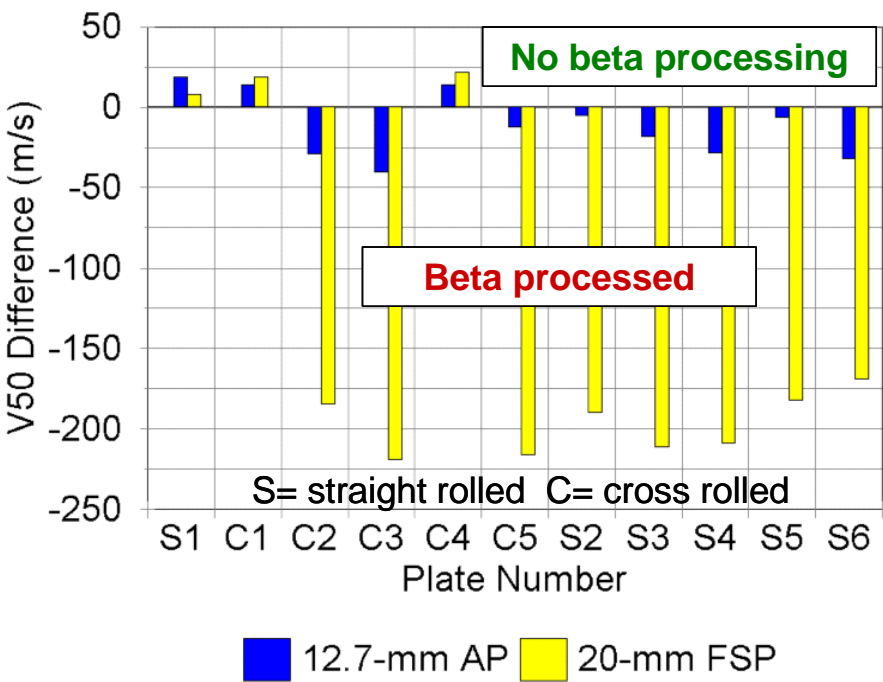


Figure 11. Beta processed Ti-6Al-4V Plate Compared to Alpha-Beta Processed Plate

higher V_{50} than straight rolling in the alpha-beta region (S1 vs. C1); however, straight rolling seemed to be slightly better than cross rolling in the beta region (C5 vs. S2). The beta-processed plates failed by a process of adiabatic shear plugging. The alpha-beta-processed plates failed by a mixed process of bulging, delamination, shearing, and spalling, which required more energy because the FSP had to burrow much deeper into the armor plate before rear surface failure occurred. The failure mode for beta and alpha-beta processed plates appeared to be the same for the 12.7-mm APM2. This observation is consistent with the relatively small differences in V_{50} performance between the beta- and alpha-beta-processed plates.

TITANIUM WROUGHT PLATE VS CASTINGS

The advantages of utilizing net shape cast titanium components for armor applications and other ballistic uses led to an examination of the ballistic performance of cast titanium as compared to wrought plate [16]. The main issue from the US Army standpoint is cost

reduction by eliminating unnecessary processing. The ballistic evaluation of cast titanium utilized ASTM 367-87 Grade 5 alloy and was compared to wrought Ti-6Al-4V plate as defined in Tables 4 and 5. The mechanical properties for the cast material are lower than the wrought plate, except for hardness and the compositions are similar. The cast titanium was also subjected to post processing procedures to include hot isostatic pressing to reduce porosity and pickling to reduce the case hardened layer and surface imperfections. The samples were impacted with armor-piercing and FSP projectiles and the results for the 20mm FSP are shown in Figure 12.

The baseline wrought data are plotted in Figure 12 as a dashed red line and the cast titanium is plotted as a solid black line. These data show the cast titanium performance to be, at best, 75% of wrought titanium and results from the reduced strengths as compared to the rolled wrought plate. The effects of post processing procedures are minimal with some possible improvement in the ballistic performance due to pickling; but the data are scattered. Conjecture would be

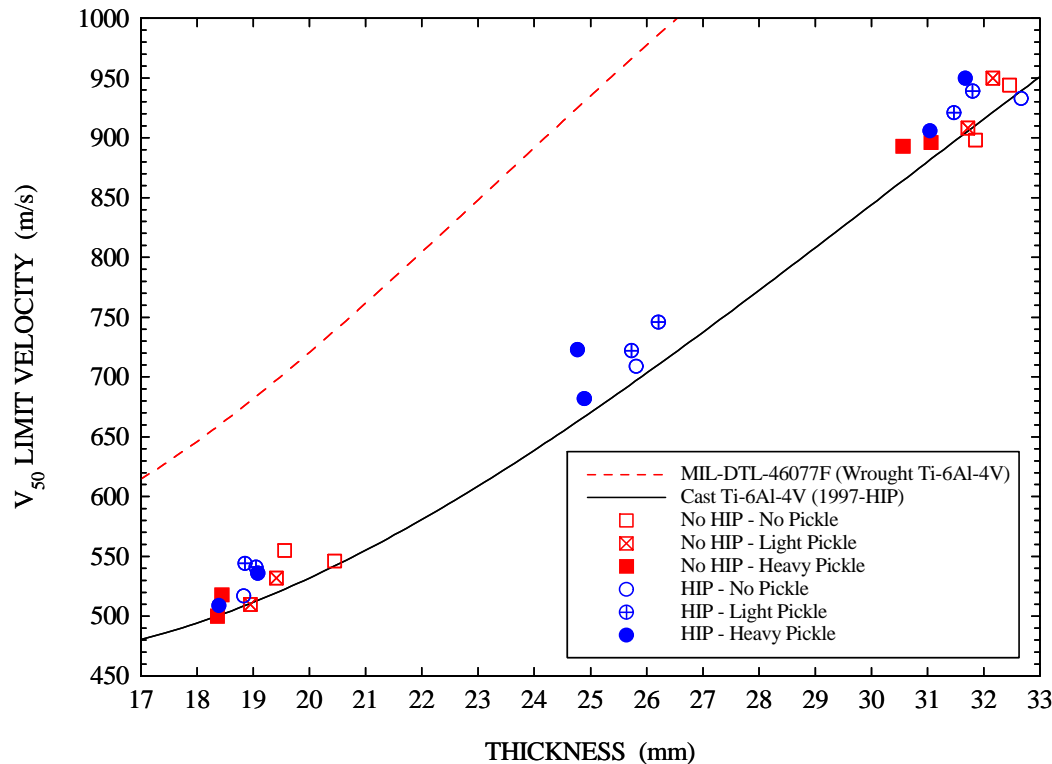


Figure 12. Ballistic Performance of 20mm FSP vs Wrought and Cast Titanium

Table 4. Comparison of Wrought and Cast Titanium Compositions

Heat #	Part ID #	Nominal Thickness (mm)	Al (%)	V (%)	Fe (%)	O (%)	C (%)	N (%)	H (%)
970139	970181	25.4	6.27	3.8	0.15	0.21	0.02	0.01	0.002
	970179	12.7							
970140	970179	12.7	6.27	3.8	0.17	0.23	0.02	0.01	0.004
	970180	19.1							
	970183	38.1							
970138	970182	31.8	6.28	3.8	0.16	0.21	0.02	0.01	0.002
	970183	38.1							
ASTM 367-87 Grade C5			5.5- 6.75	3.5- 4.5	0.40 max	0.25 max	0.10 max	0.05 max	0.015 max

Table 5. Mechanical Properties of Cast and Wrought Titanium

Heat #	Part ID #	Nominal Thickness (mm)	Tensile Properties			Hardness (BHN)
			0.2% YS (MPa)	UTS (MPa)	Elong (%)	
970139	970181	25.4	885	989	10.0	318
	970179	12.7				
970140	970179	12.7	900	1024	11.0	315
	970180	19.1				
	970183	38.1				
970138	970182	31.8	879	981	10.0	299
	970183	38.1				
ASTM 367-87 Grade C5			825 min.	895 min.	6 min.	365 max.

that any post process that homogenizes the surface, particularly the back of the casting could decrease crack initiation points when in tension. The use of cast components will require 20-25% thicker cross-sections

over wrought plate. In complex shapes, casting may be advantageous when compared to steel castings that suffer the same issues.



Figure 13. Titanium Forging of Bradley M2A2 Commanders Hatch

TITANIUM FORGINGS

Figure 13 shows a single application of the forging of the titanium for military application for ground vehicles. The commander's hatch for the M2A2 Bradley is a very intricate shape and a titanium forging resulted in providing a lower weight and ballistically equivalent hatch.

TITANIUM COMPOSITES/LAMINATES

The use of titanium as a standalone armor material has ballistic disadvantages due the breakout effects of

adiabatic shearing. Similar effects are found with high hard steels. For this reason, these types of metals can be backed with ductile or compliant materials as a laminate to create a much higher ballistic performance than the individual materials. This is shown in Figure 14 where a titanium plate is mechanically attached to an aluminum back plate. The backing could also be fiber composites such as S2 glass, Kevlar Aramids, or polyethylene Dyneema/Spectrashield composites. The harder front face erodes the projectile and the rear ductile layer captures the fragment. Figure 15 conceptually shows a titanium dual hard metallurgically bonded laminate similar in concept to dual hard steel. These type of

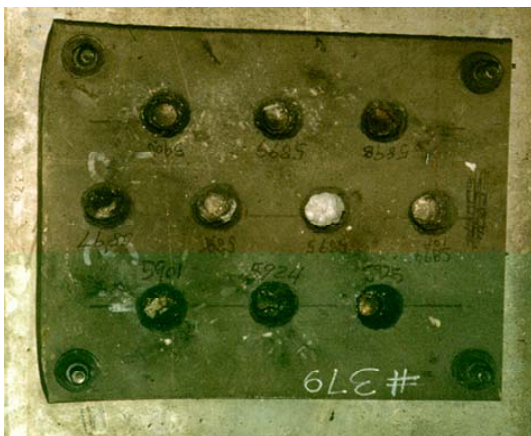


Figure 14. Titanium Wrought Plate Bolted to an Aluminum Rear Plate

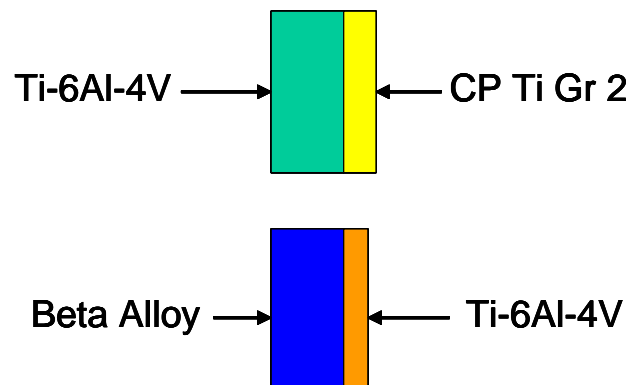


Figure 15. Dual Hard Titanium Concepts

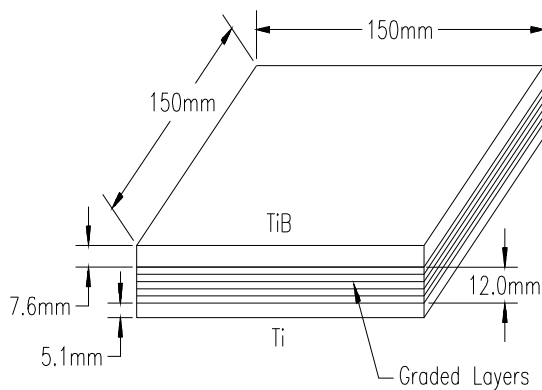


Figure 16. Functionally Graded Titanium Monoboride/Titanium Plate

laminates would take advantage of mechanical properties and ballistic response of the individual components to make a superior ballistic material that could be fabricated as a single plate.

The development of functionally graded materials (FGM) using ceramics and metals offers higher performance than metal laminates or even dual hardness metal laminates. BAE Advanced Materials, under contract to ARL, has developed a process to hot-press large near net-shape FGM tiles in a single stage utilizing titanium and titanium/titanium diboride (TiB_2) powder mixtures, forming a titanium monoboride (TiB) hard face/titanium metal substrate that grades through intermediate layers [17]. As seen in Figure 16, the TiB ceramic is formed through a reaction sintering process between the TiB_2 and titanium powders during the hot-press phase. TiB is densified as a cermet (ceramic in a metal matrix) to aid in fabrication. A major development in the process was overcoming the inherent thermoelastic properties of the constituent layers and the

resultant stresses that arise from the differences in thermal expansion coefficients and elastic moduli of the layers. Analytical and finite element modeling techniques were used to determine the residual stresses and modify the processing parameters. The resultant tiles produced to date are among the largest functionally gradient materials produced in the world by a practical process and represent advancement in this technology area.

Another more advanced ceramic laminate is hot isostatically pressed ceramic tiles in titanium matrices. The titanium matrix maintains a compressive load on the ceramic, thereby allowing full advantage of the large dynamic compressive strengths of ceramics [18]. The left image of Figure 17 shows the defeat of a long rod tungsten alloy penetrator by a defeat mechanism called “interface dwell; the projectile is being totally consumed at the metal ceramic interface with little damage to the ceramic. One fabrication method for incapsulation in a metallic structure is to hot isostatically press the titanium around the ceramic as seen in the right two images.

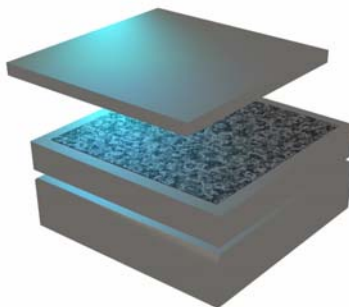
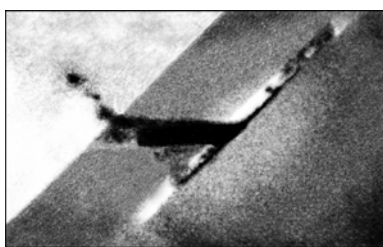


Figure 17. Hot Isostatically Pressed Ceramic in Titanium Matrices

CLASS 4 TITANIUM ALLOYS UNDER MIL-DTL-46077G

MIL-DTL-46077G was created to provide an incentive to the titanium industry to develop non-aerospace grades of ballistic titanium. The chemistries of Class 1 and Class 2 mirror that of Ti-6Al-4V ELI and standard grade 5. Class 3 allows for higher levels of iron and oxygen and Class 4 goes a step further by removing the requirements for aluminum and vanadium. Class 4 titanium must still fall into the Alpha-Beta range of alloys and meet all other mechanical and ballistic requirements for the other classes of the MIL spec.

The application of titanium into ground platforms has historically been greatly limited by the competition from the aerospace industry and the cyclic cost variations as demand for Class 1 and 2 Ti-6Al-4V alloys changes with material requirements. As density and strength are primary driving factors in the ballistic performance of titanium, Class 4 titanium alloys offer the potential for new ballistic applications. The development and application of non-Ti-6Al-4V alloys also offers large advantages due to the reduced use of higher cost alloying elements. ARL considers this technical direction as the best opportunity for increasing titanium applications for ground applications in the future.

ARL has examined a number of Class 4 titanium alloys for potential applications; examples include TIMET

62S™ and ATI 425-MIL™. The latter alloy has shown similar ballistic performance to the standard Class 2 Ti-6Al-4V alloy, but utilizes Iron in place of some higher-cost Vanadium as a beta stabilizer. The alloy can also be both cold and hot-worked and this capability has shown advantages in a wide variety of developmental applications. Fabrication using Class 4 alloys may increase perceived production issues, such as qualification costs associated with legacy vehicle production, but this direction offers potential to increase applications to both commercial and military platforms.

CURRENT APPLICATIONS OF TITANIUM IN GROUND SYSTEMS

The use of titanium in military platforms has been driven by two related requirements, increased ballistic performance when used as an armor or weight reduction to increase mobility or meet tactical requirements. Either application takes advantage of the unique density and strength properties of this metal. As an armor, the performance has been documented in previous sections; however, the use of titanium as a weight reduction technique is also employed. The earliest use of titanium in a combat vehicle is shown in Figure 18 of a 1960 Detroit Arsenal prototype of a titanium cab on an ONTOS tracked vehicle [19]. While the research on titanium armors continue with periodic armor designs, the main drawback to the use of titanium remains the relative cost to other metals. The majority of the

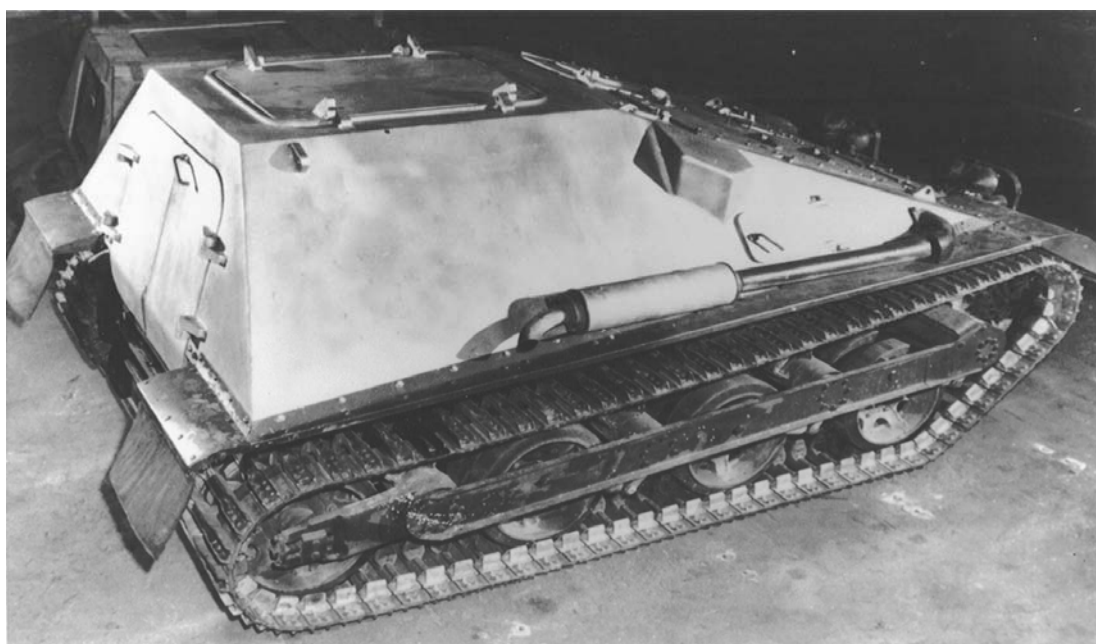


Figure 18. 1960 Detroit Arsenal Titanium Cab on an ONTOS Tracked Vehicle

structure and armor components for the world's combat vehicles remain steel or aluminum based and large amounts of aluminum appliques have been procured for add-on armor kits. The advent of low cost titanium grades and increased cost of more advanced materials such as composites and ceramics has allowed the use of

titanium alloys as cost effective alternatives. The following paragraphs will illustrate some applications of titanium to currently field combat vehicles and weapon systems; the discussion is not comprehensive and some applications cannot be discussed in this forum.

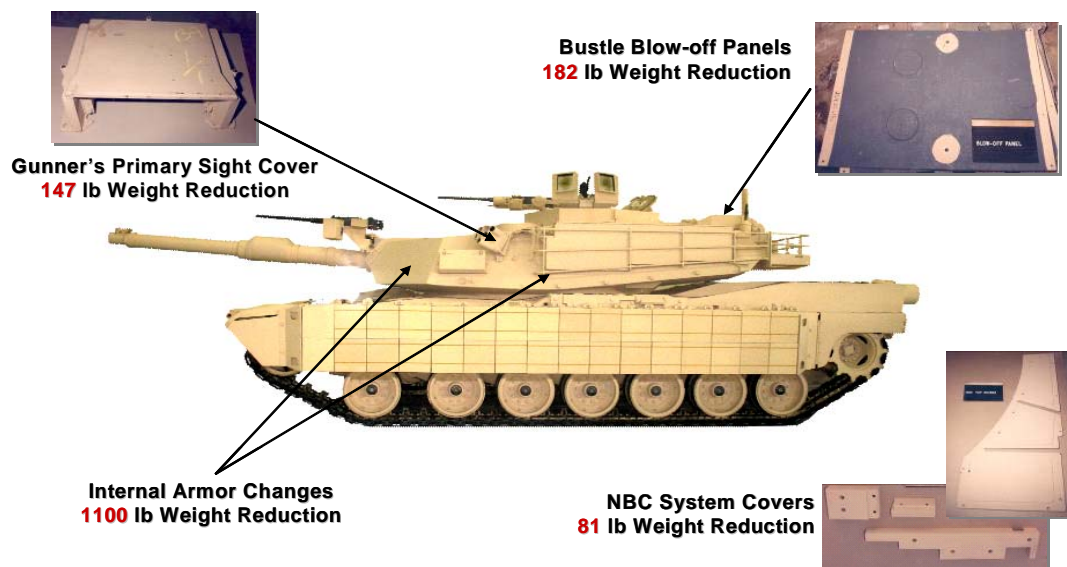


Figure 19. Titanium Weight Reduction Program for M1A2 Abrams Battle Tank

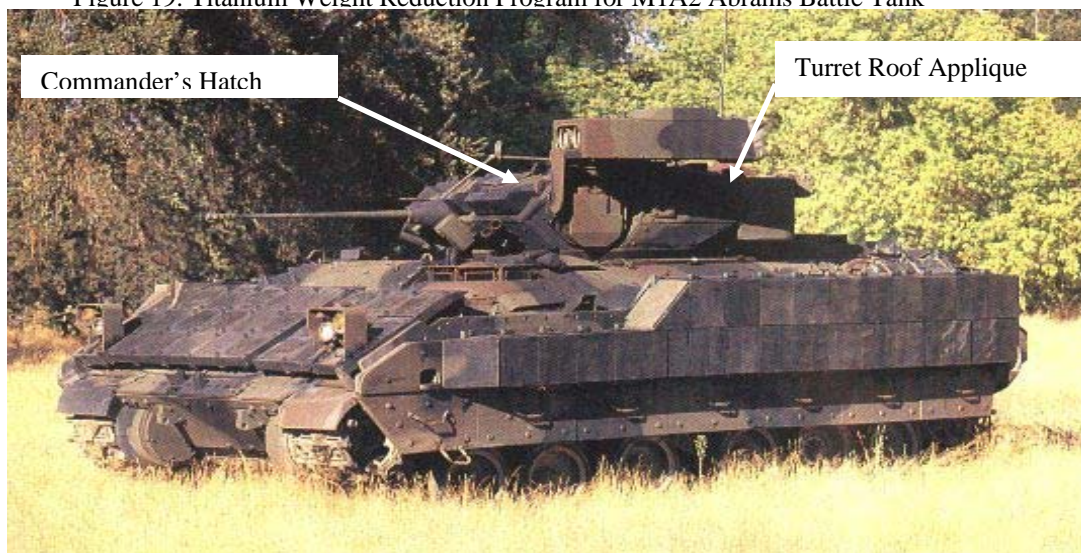


Figure 20. Titanium Commanders Hatch and Roof Applique on M2A2 Bradley Fighting Vehicle

One of the best illustrations of titanium on a current legacy system is shown in Figure 19 on the M1A2 Abrams tank where a concerted effort was made to reduce weight of components on the chassis [20-21]. While this weight reduction program envisioned a larger

replacement of components, these four areas reduced combat weight by over 1500 lbs without loss of function or protection. Figure 20 shows the M2A2 Bradley Fighting Vehicle and two uses of titanium have been incorporated into design. The commanders hatch is a



Figure 21. Ultra-light Weight M777A1 Towed Howitzer Utilizes Extensive Titanium Castings

titanium forging and a titanium roof appliqué was added for increased protection. The Reactive Armor Boxes on the sides were also designed to utilize titanium sheet as a replacement for sheet metal in the box construction.

The Ultra-light weight Field Howitzer, designated M777A1 in the USA, shown in Figure 21, was selected in 1997 by a joint US Army/Marine Corps initiative to

replace the existing inventory of M198 155mm towed howitzers [22]. The construction of the M777A1 makes extensive use of titanium and titanium castings, enabling a weight reduction of 3,175kg (7,000lb) compared to the M198 howitzer which it replaces in the US Army and USMC inventory.



Figure 22. BAE Pegasus Titanium Wheeled Prototype



Figure 23. Future Combat Vehicle Titanium Hull Prototype

Future platforms will utilize a range of advanced light weight materials and low cost titanium has a role in providing high strength, low weight structures and components. These can be seen in a number of prototypes developed by the US Army and their contractors. Figure 22 shows the Pegasus electric drive wheeled prototype developed by BAE Systems that utilized both a lower and upper titanium welded structure [23]. The vehicle incorporated a composite rear space frame armor as well as the capability to mount a composite appliqué. This was the first full titanium vehicle prototype since the ONTOS vehicle in 1960. The latest prototype titanium vehicle structure was an early Future Combat Vehicle hull section that was used to test composite armors (Figure 23) [19]. The lower body and nose sections were fabricated from Military Specification MIL-DTL-46077G Class 3 low cost titanium and were mated to a composite and space frame composite upper hull section. The vehicle was subjected to extensive ballistic testing and shock loading to measure the vehicle response.

CONCLUSIONS

This paper has provided an overview on the use of titanium in military ground systems. The emphasis has been to examine the design and processing aspects in the

application of this lightweight, high strength metal. With major emphasis on lightening future ground platforms, low cost grades of titanium can provide both structural and ballistic solutions. The biggest issues are cost tradeoffs versus ballistic and structural performance and continued advancements in titanium processing are important to maintain titanium as a metal choice for future military systems.

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23. Figure provided Courtesy of BAE Systems, Santa Clara, CA



THE DESIGN AND APPLICATION OF TITANIUM ALLOYS FOR US ARMY PLATFORMS

TITANIUM 2009

MILITARY PANEL

Waikoloa, Hawaii

13-16 September 2009



TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

William. A. Gooch

U.S. Army Research Laboratory

Weapons and Materials Research Directorate

Aberdeen Proving Ground, MD 21005-5066

THIS PRESENTATION IS UNCLASSIFIED/PUBLIC DOMAIN

- Titanium was first examined for armor applications in 1950 by the Watertown Arsenal, with the Ti-6Al-4V becoming the main alloy of interest
- The main advantage of titanium relates to the lower density (lower areal density) at equal or higher strengths than rolled homogenous armor steel of equal thickness (23.2 vs 40.8 psf for 1" board foot ~43% weight reduction)
- The introduction of Military Specification MIL-DTL-46077 initially set two classes of Ti-6Al-4V that had similarities to commercial specifications, but the application potential for titanium significantly increased with the introduction of Class 3 and 4 alloys that offered lower cost through increased oxygen levels, greater scrap content and lower cost processing technology
- This presentation will examine some of the processing issues and the specific impact on the use of titanium for weight reduction and/or increased ballistic protection for ground platforms
- The presentation will end with an overview of some current and proposed future applications of titanium in military ground vehicles

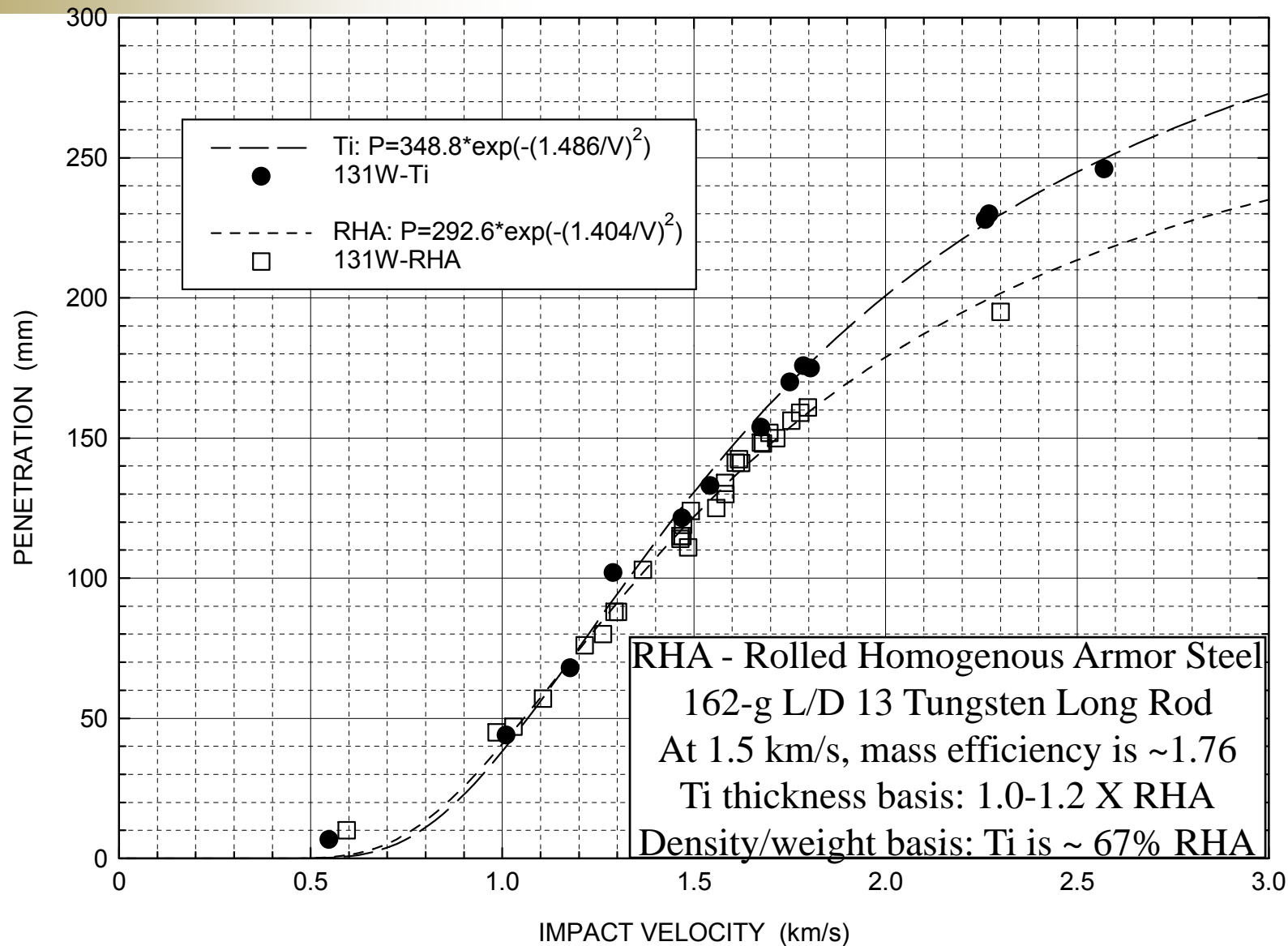


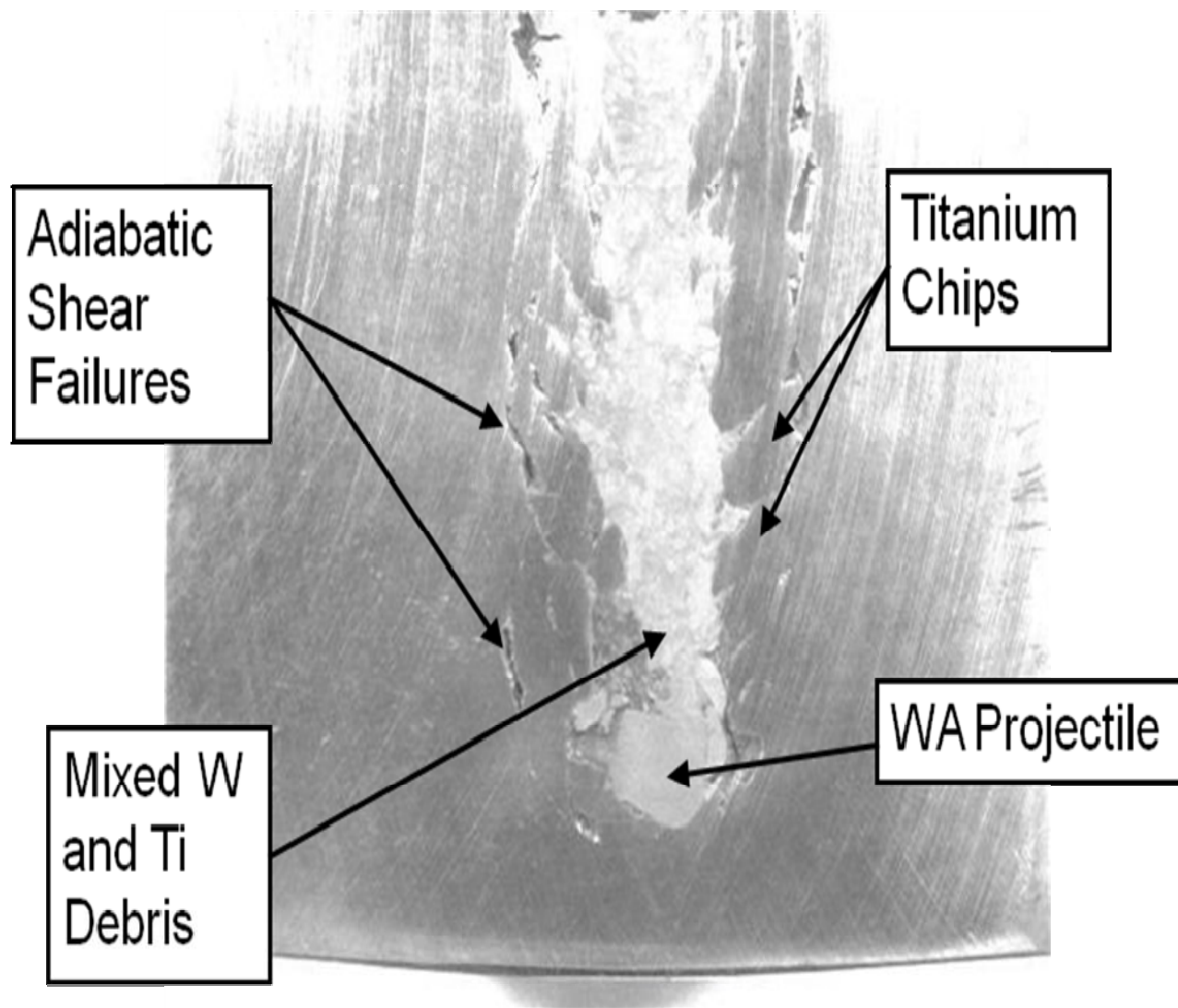
MIL-DTL-46077 Armor (Version F & G)



	Chemistry	Max. O ₂ Content	Comments
Class 1	6AL- 4V	0.14%	<i>ELI-</i> 10% Elongation Min.
Class 2	6AL- 4V	0.20%	<i>Common Armor</i> 6% Elongation Min.
Class 3	6AL- 4V	0.30%	<i>High Scrap Content</i> Weld & cold temp issues
Class 4	Not Limited	0.30%	<i>For future developments</i>

**All 4 classes have the same min. strength
and ballistic requirements.**

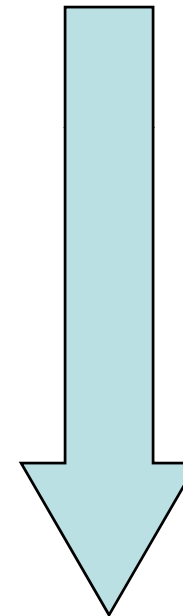
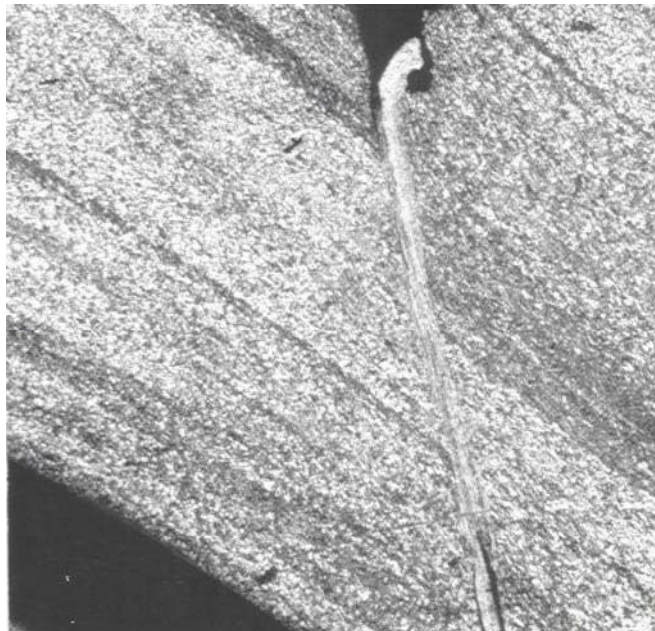
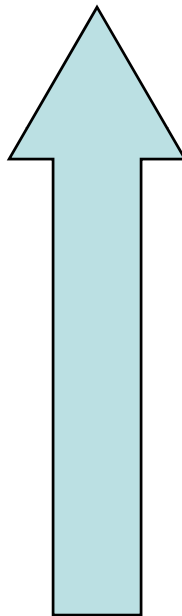




Strain causes
localized heating



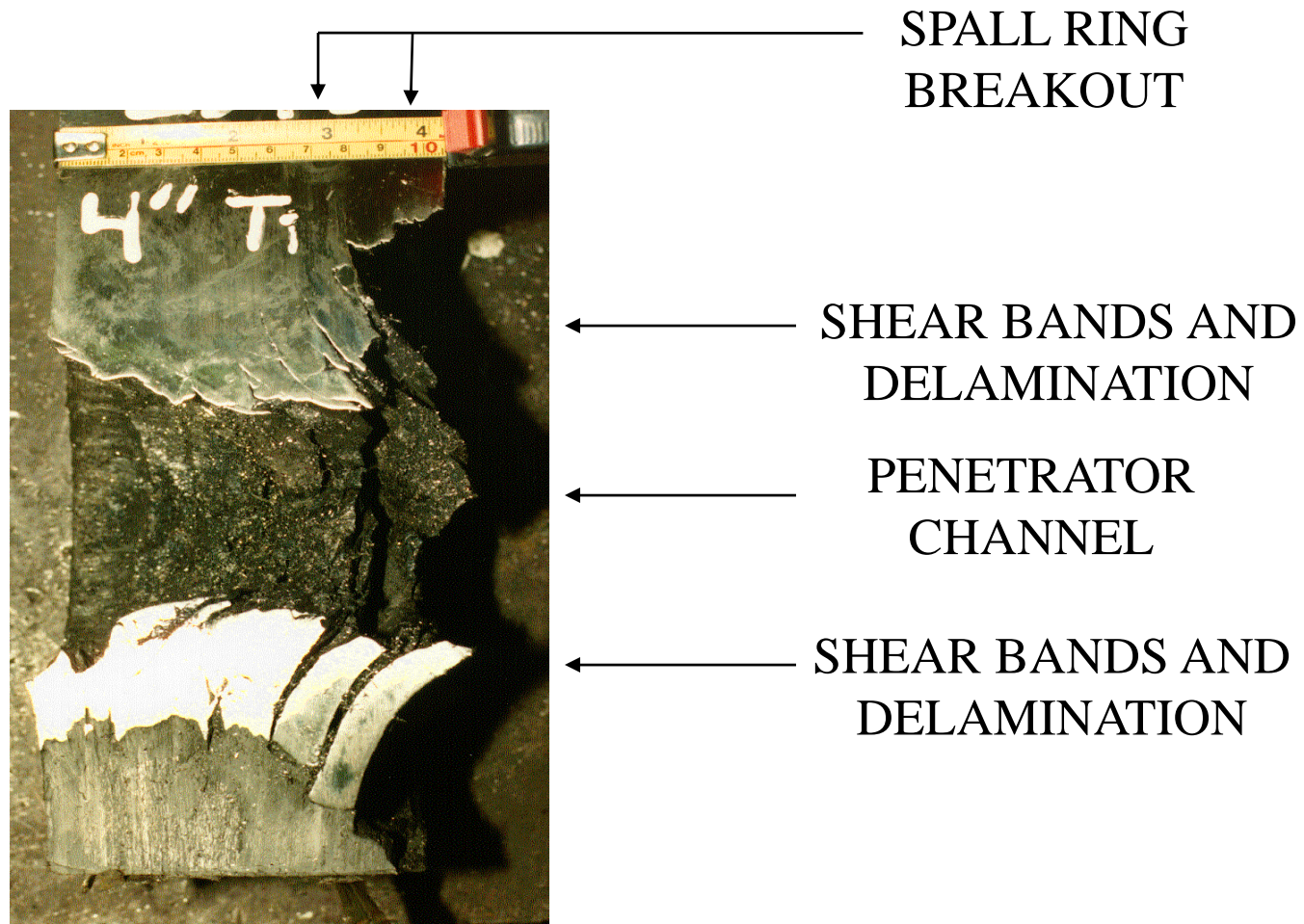
Heat cannot
dissipate

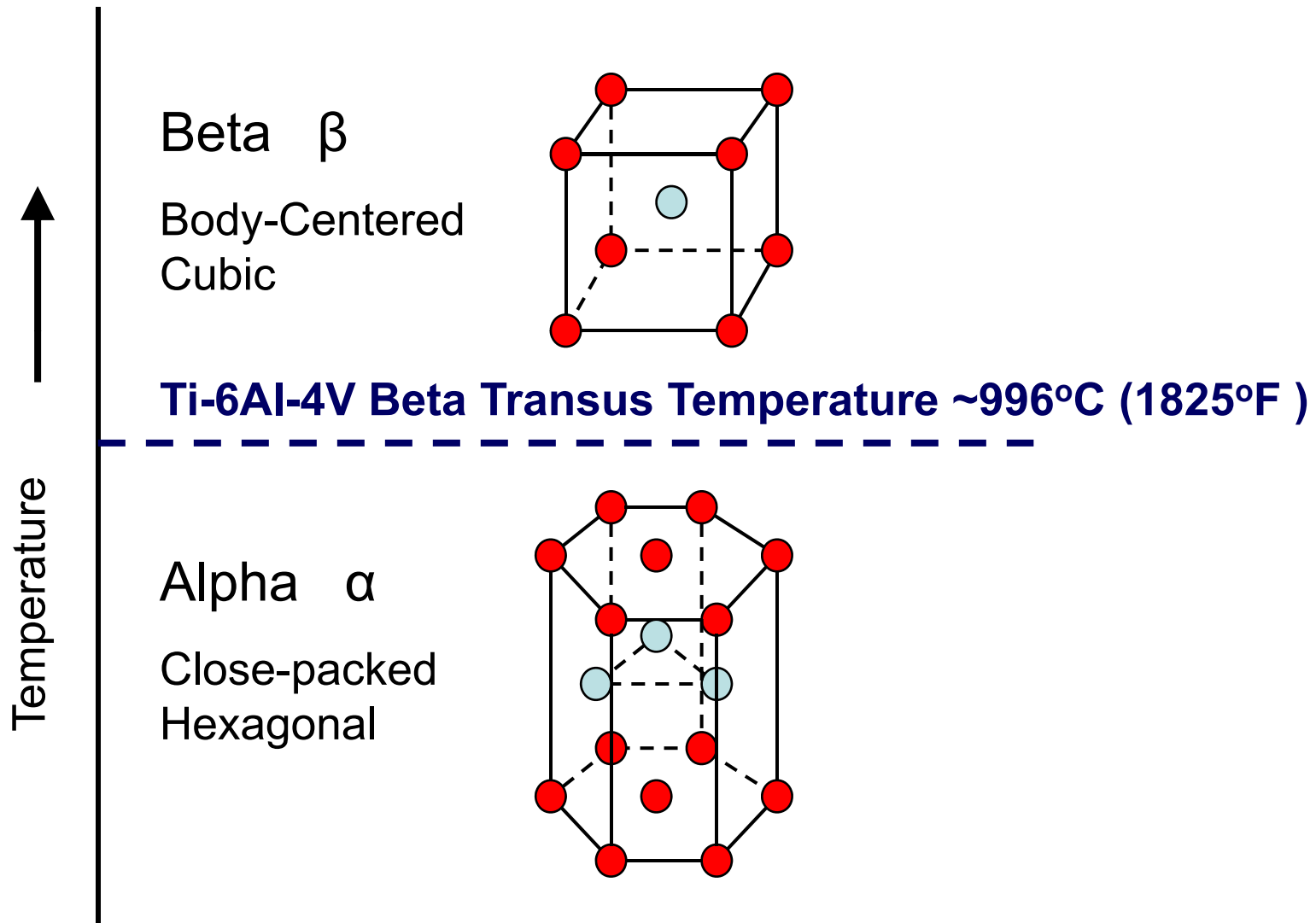


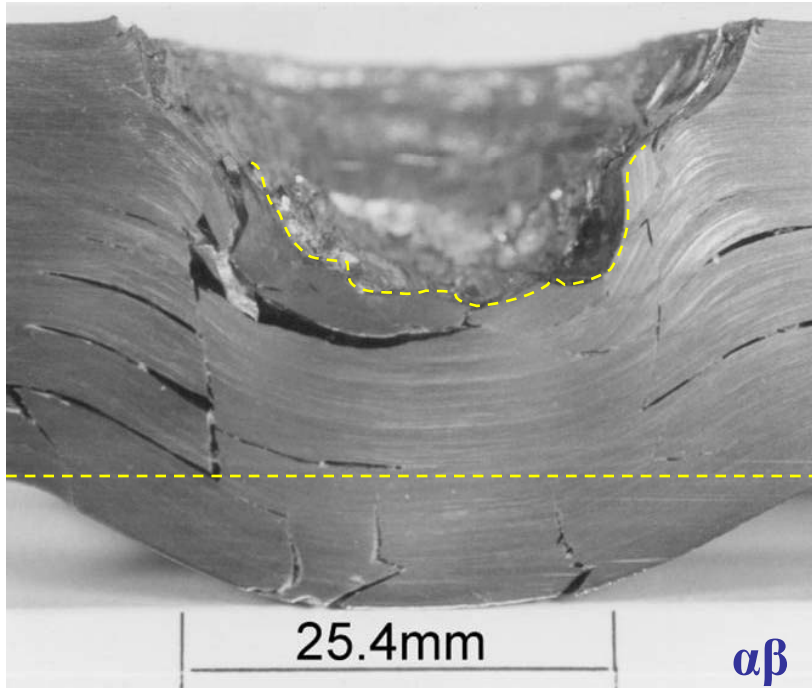
Additional strain
in soft areas



Material softens

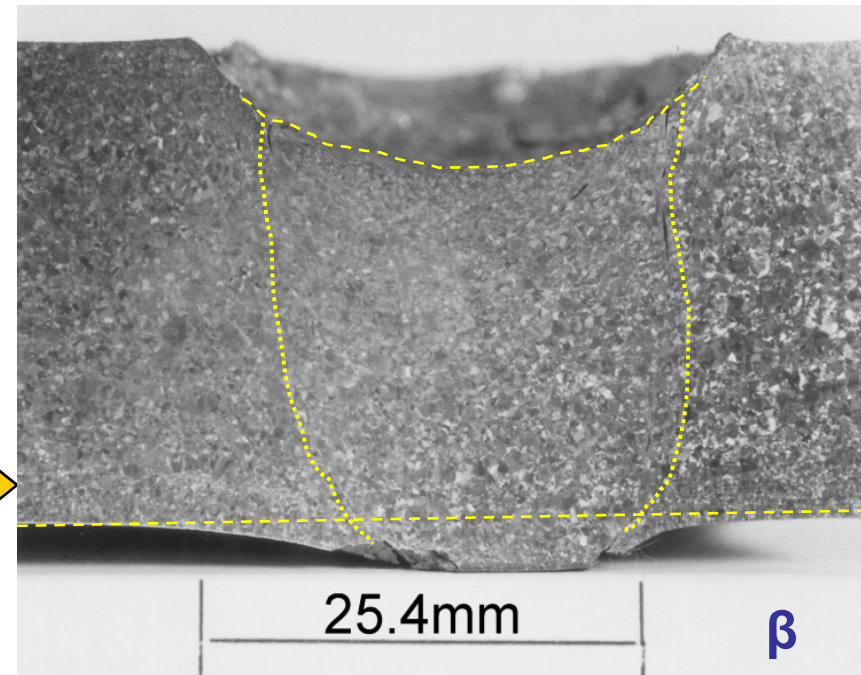






Failure by a mixed
process of bulging,
delamination, shearing,
and spalling

Failure by
low-energy
plugging



- Beta processing can be controlled or avoided in wrought plate and forgings.
- Beta processing is unavoidable for **welds**, **castings**, and some powder metallurgy processes.

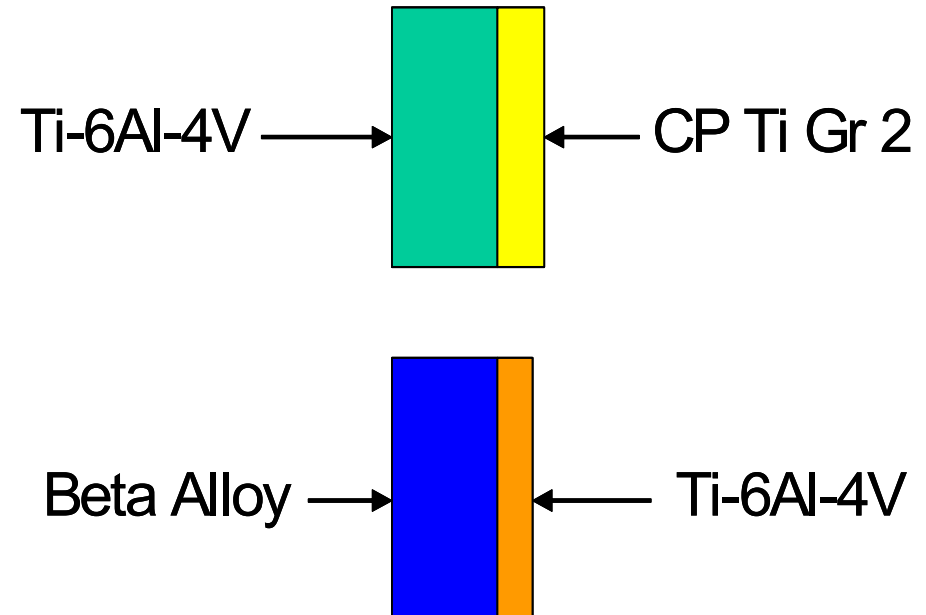


Forged Commanders Hatch for
M2A2 Bradley

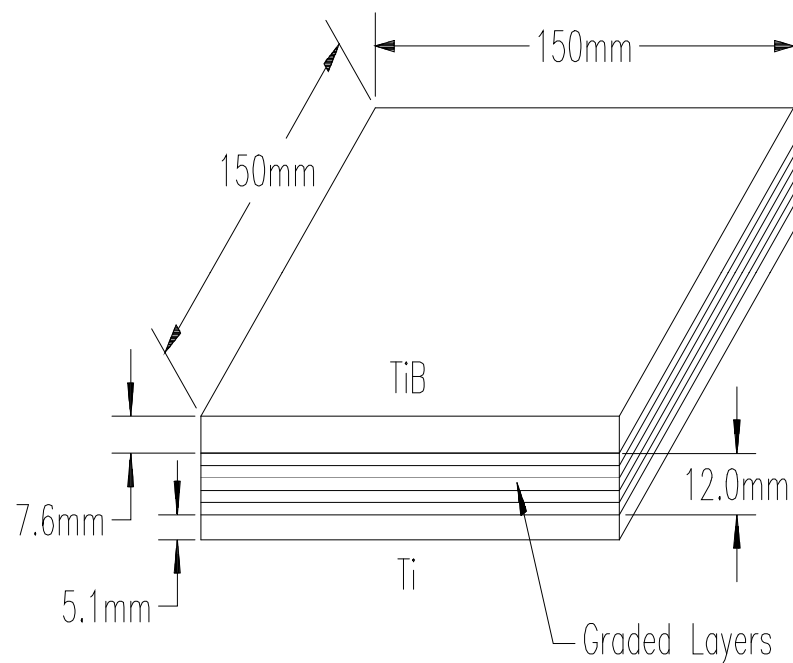
Designs must include additional thickness (~10-20%) to offset reduced performance.

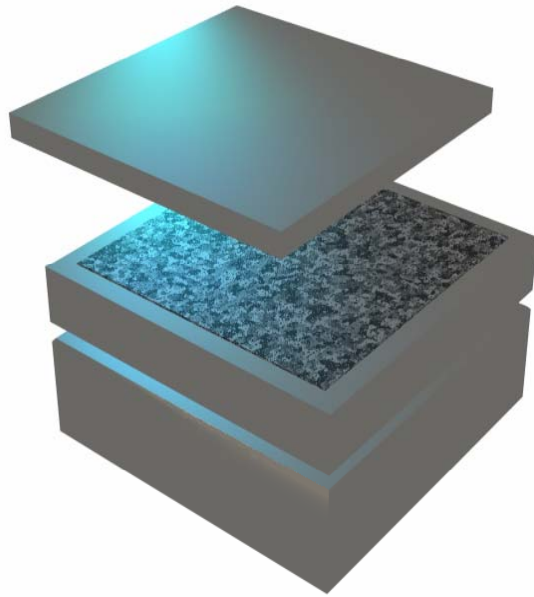


Titanium Wrought Plate Bolted to
an Aluminum Rear Plate

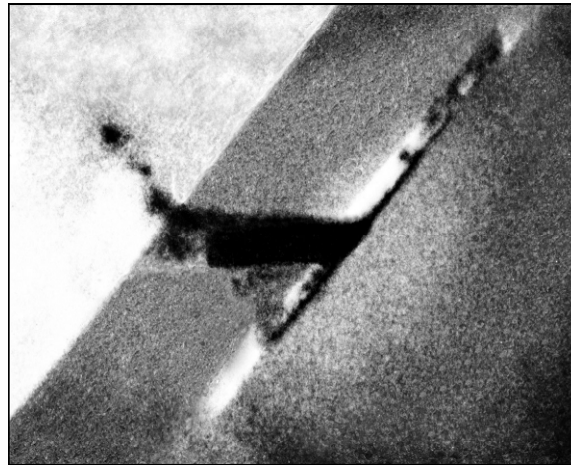


Dual Hard Titanium Concepts





Titanium/Ceramic
Preform before HIP

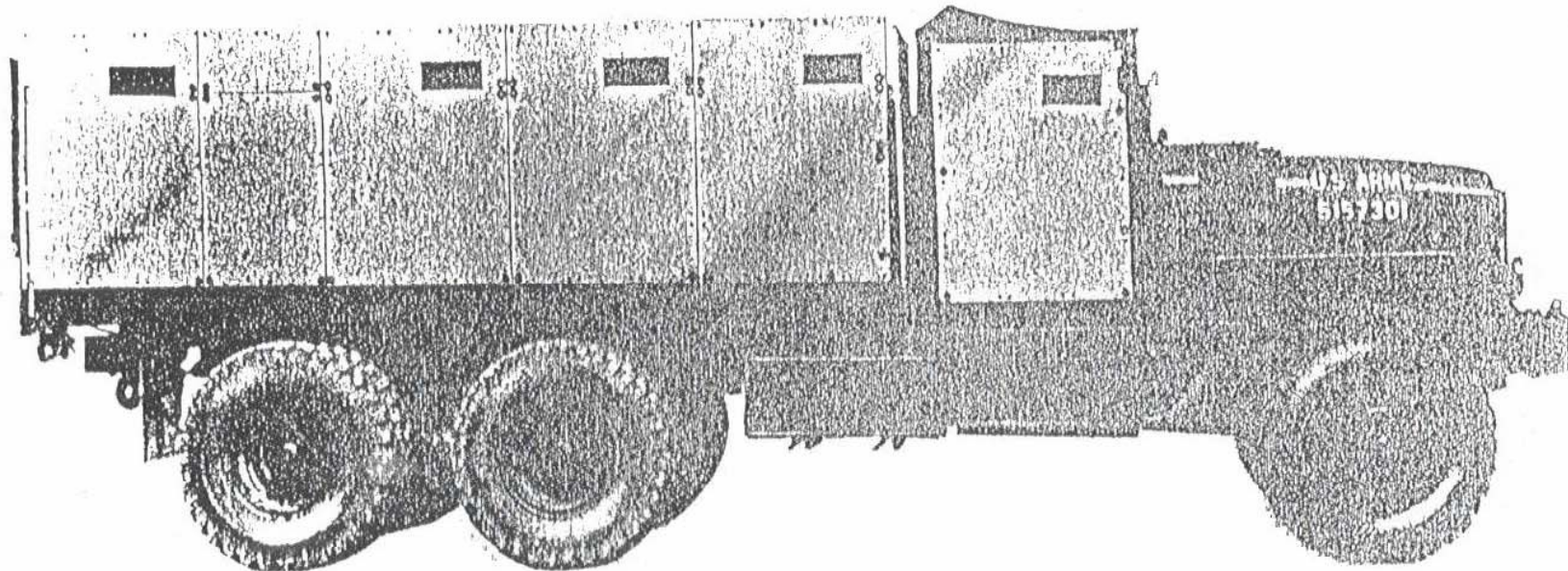


Dwell on Ceramic by Long
Rod Penetrator

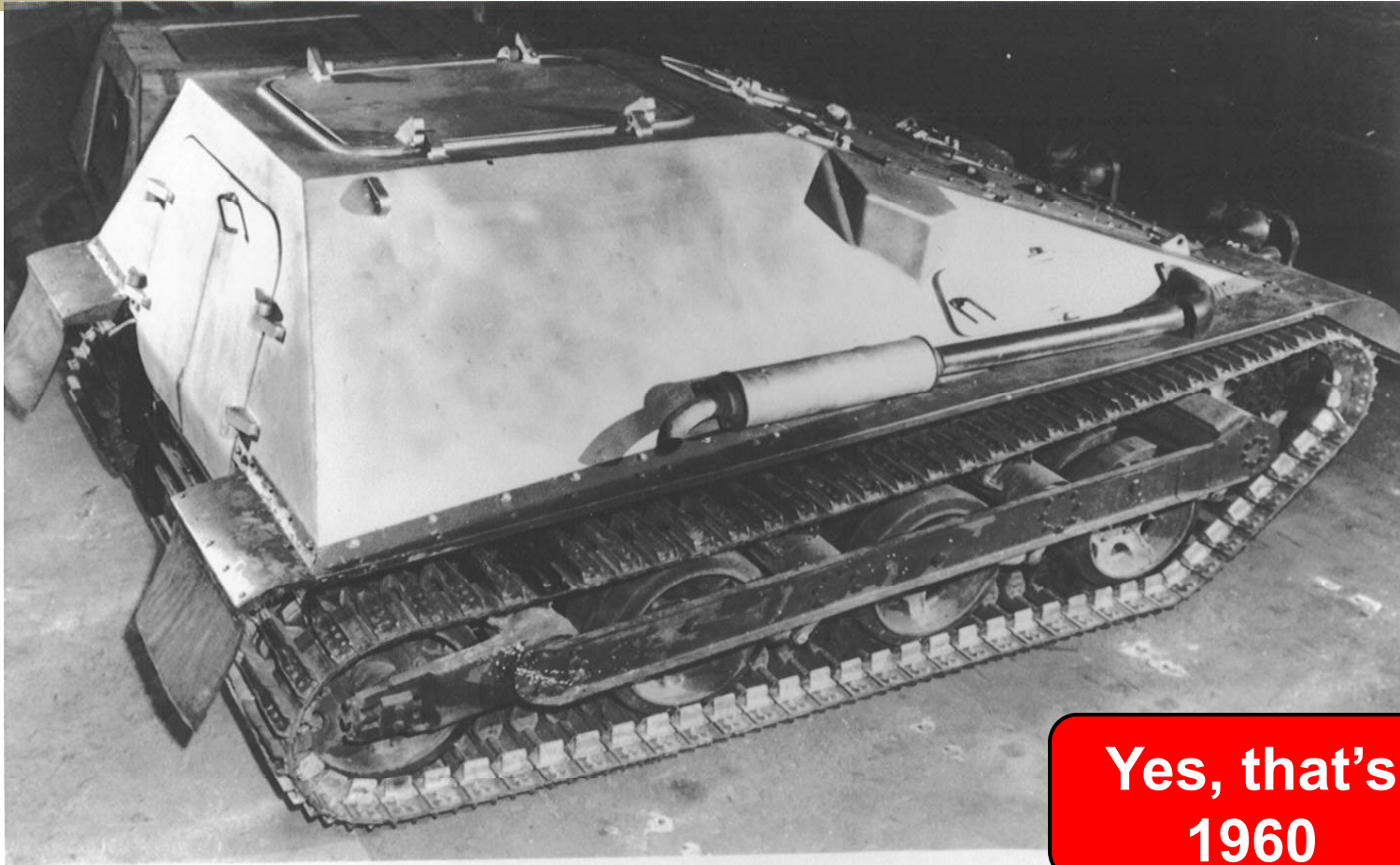


Post Impact Condition

Proposed as modular armor for 5 Ton Trucks
during the Korean War



Steel used due to cost and availability issues.

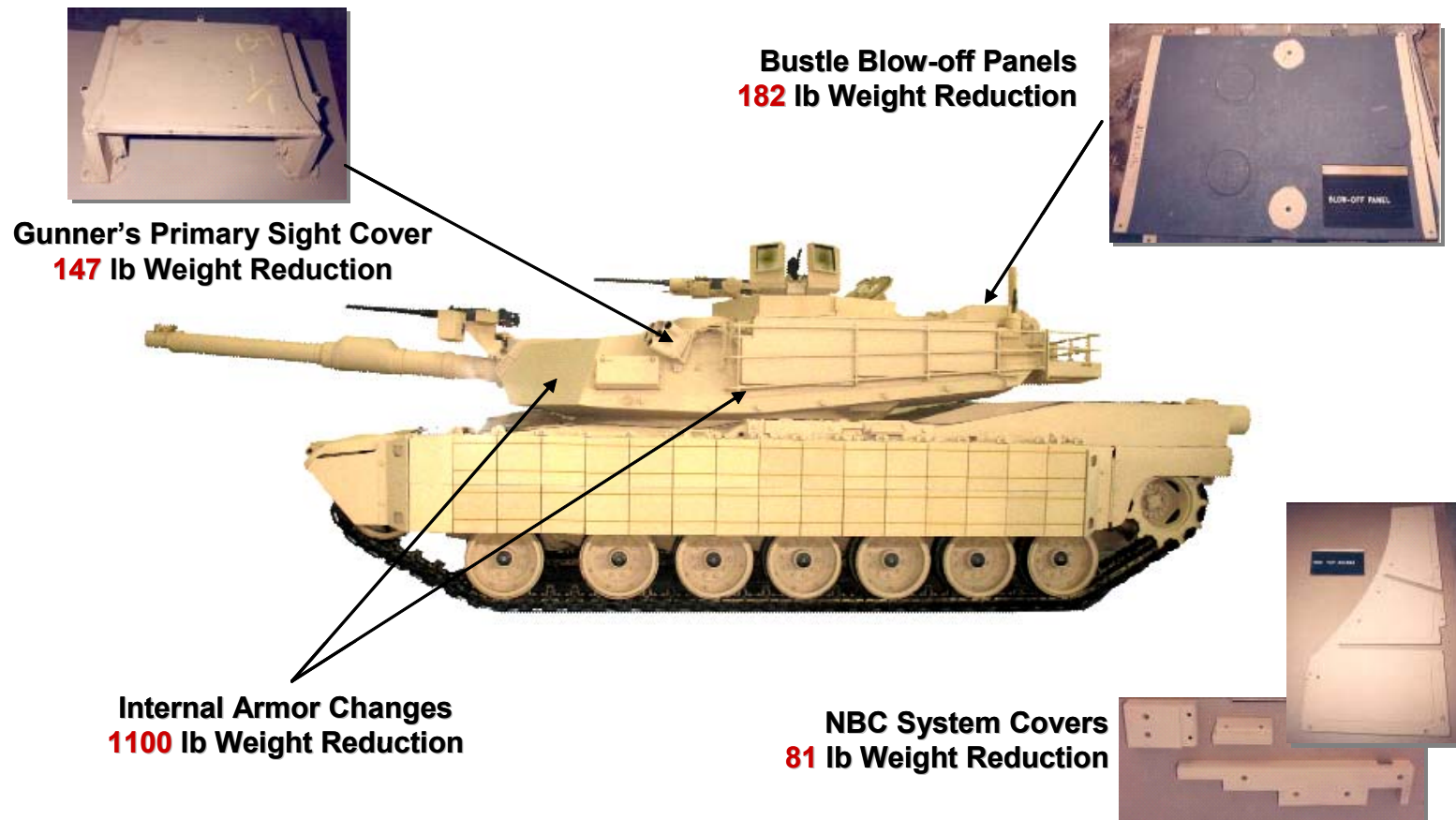


Yes, that's
1960

—DETROIT ARSENAL—
NEG NO. 64132 DATE 7 Sept 60

Titanium Welded Cab on ONTOS Vehicle

Titanium Weight Reduction Program for M1A2 Abrams Battle Tank



GDLS >1500 lbs weight savings

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Titanium Commander Hatch and Roof Applique on M2A2 Bradley Fighting Vehicle



Ultra-light Weight M777A1 Towed Howitzer Utilizes Extensive Titanium Castings and Plate



>7000lbs savings over M198

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

BAE Pegasus Titanium Wheeled Prototype



Future Combat Vehicle Titanium Hull Prototype





Class 4 Titanium Armor under MIL-DTL-46077G



- The most promising direction for increased titanium armor applications is through the development and production of Class 4 titanium alloys that have commercial applications .
- These alloys can have lower production costs through advanced processing techniques such as plasma or electron beam melting, can contain higher scrap content, higher oxygen content and can utilize lower cost alloying elements.
- These alloys do not compete with commercial aerospace alloys that have a variable demand cycle competing with ground system applications.
- ARL has examined some Class 4 titanium alloys such as Timet Ti-62S™ and ATI Ti-425™.
- The ATI Ti-425™ has shown similar ballistic performance to Class 2 Ti-6Al-4V, with reduced aluminum and vanadium alloys with Fe added as a additional Beta stabilizer
- Other alloys should be available in the titanium community for testing