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

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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 the 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.

## 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.

## 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$^{o}$ 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$^{o}$ 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$^{o}$ 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 these ballistic tests. 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. Titanium has poor hardenability in thick sections and cannot be rapidly quenched. However, excellent mechanical properties can be developed in 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.

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 Melt for both Class 3 and 4. Armor grade titanium has a greater tolerance to oxygen content than other applications. Class 4 titanium, unlike Class 1-3, allows alternate alloys to be utilized for armor applications.

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

| | Chemistry | Max. $O_2$ Content | Comments |
|---|---|---|---|
| Class 1 | 6AL- 4V | 0.14% | ***ELI-***<br>10% Elongation Min. |
| Class 2 | 6AL- 4V | 0.20% | ***Common Armor***<br>6% Elongation Min. |
| Class 3 | 6AL- 4V | 0.30% | ***High Scrap Content***<br>Weld & cold temp issues |
| Class 4 | Not Limited | 0.30% | ***For future developments*** |

## 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.

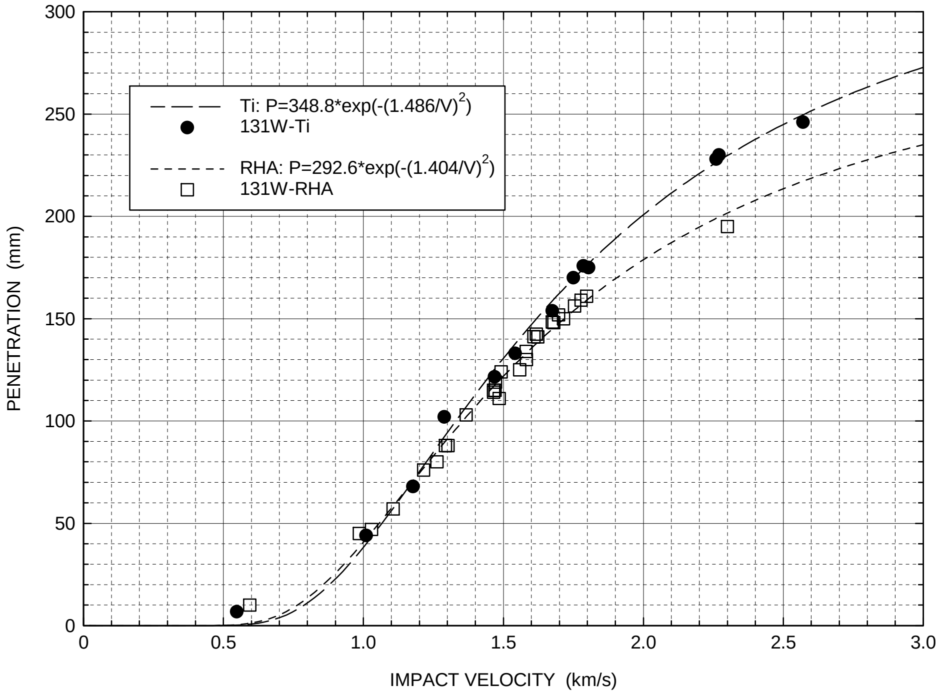


Figure 1. Penetration of a Tungsten Long Rod Penetrator into RHA and Titanium

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 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 due to shear-induced strain localizations due to 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

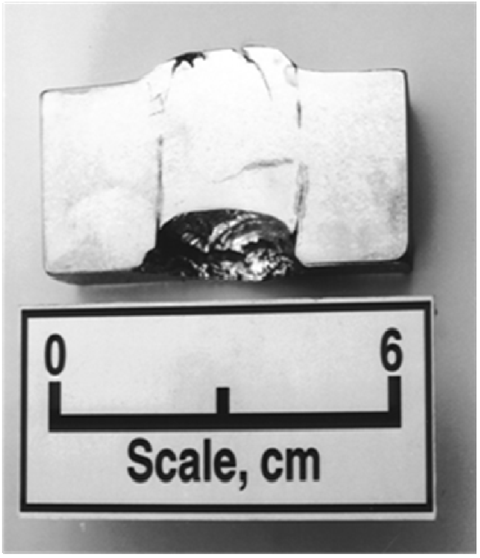


Figure 2. Cross-section of Impact Crater from 20-mm FSP for Beta Processed Plate

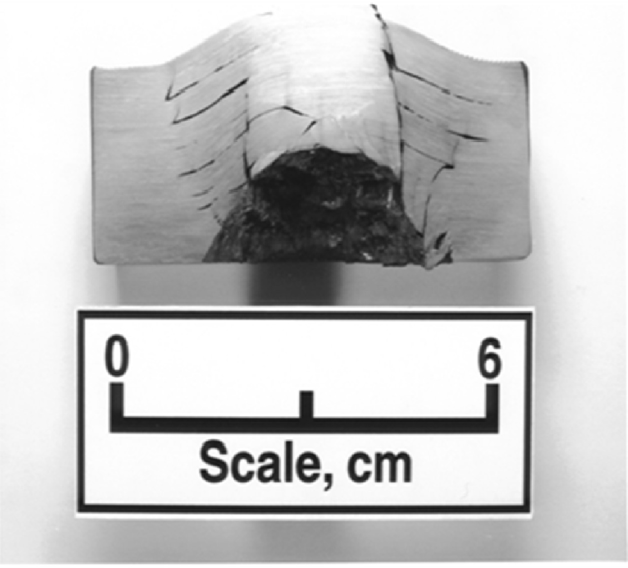


Figure 3. Cross-section of Impact Crater from 20-mm FSP for Alpha-Beta-Processed Plate

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.

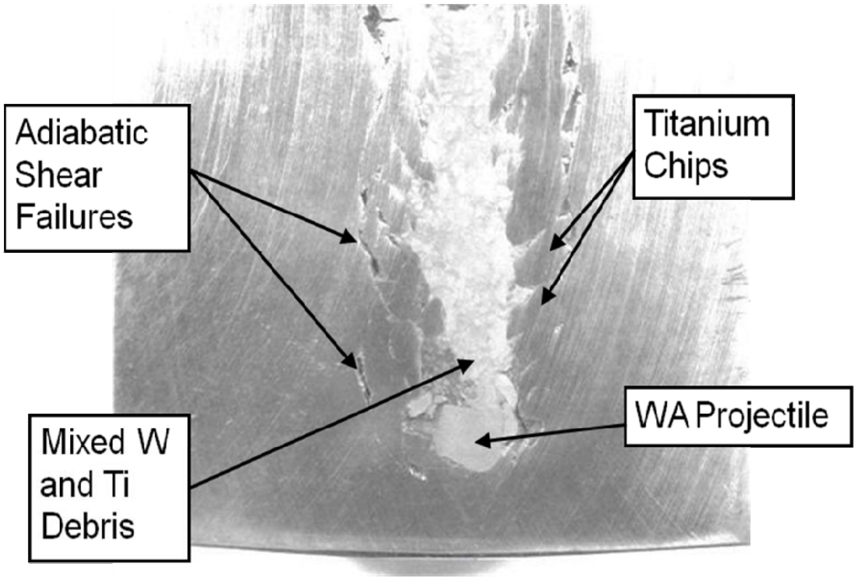


Figure 4. Deep Penetration of a Tungsten Long Rod Penetrator into Titanium showing Adiabatic Shear Bands

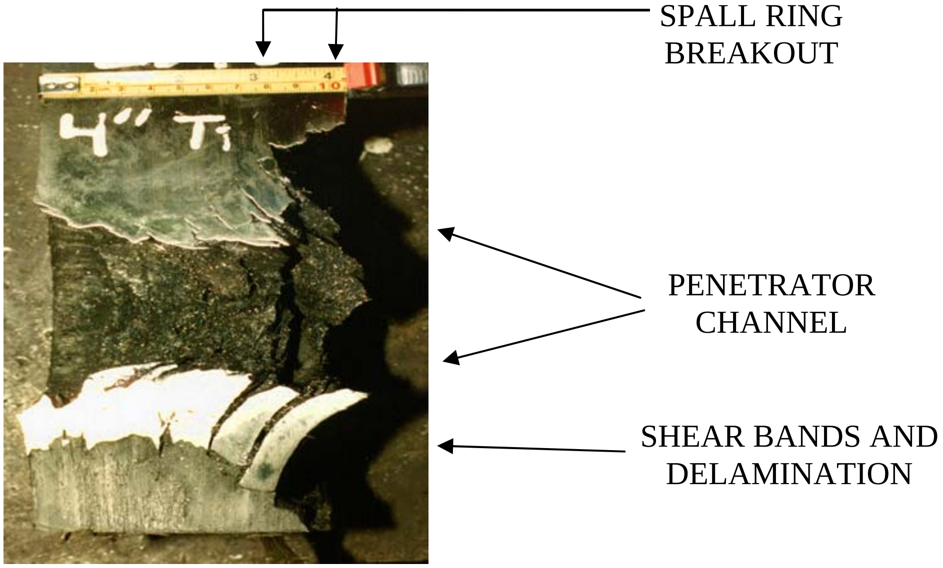


Figure 5. Spall Plug Breakout of a 100mm (4.0") Titanium Plate after Perforation by a Long Rod Penetrator

## 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

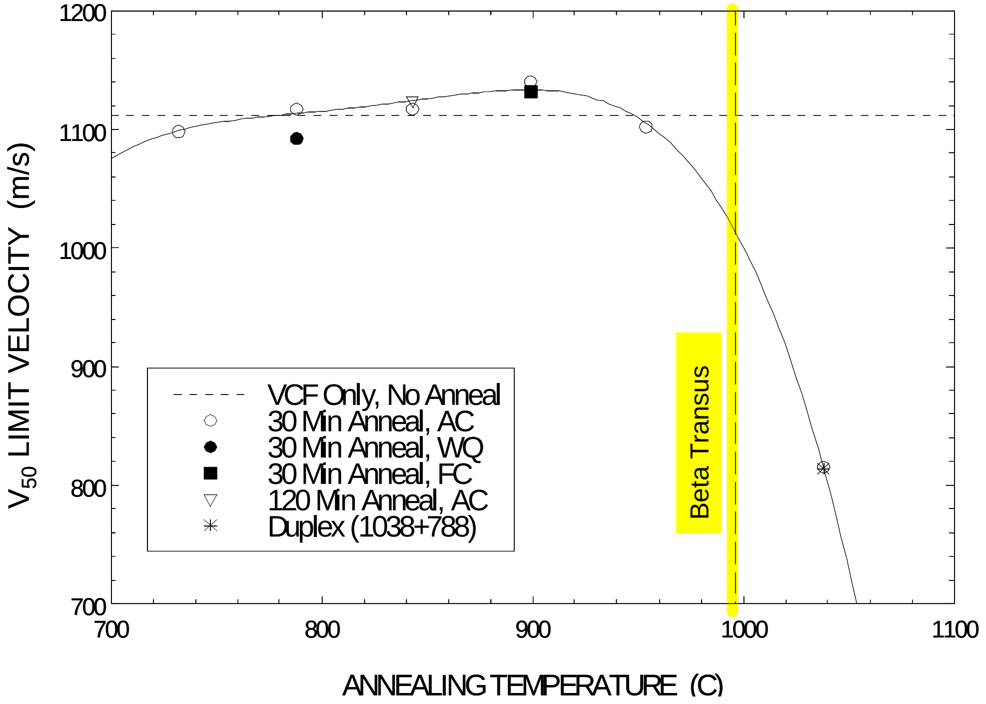


Figure 6. Effect of Annealing Temperature on Ballistic Performance

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 $900^{o}$C to obtain the highest performance.

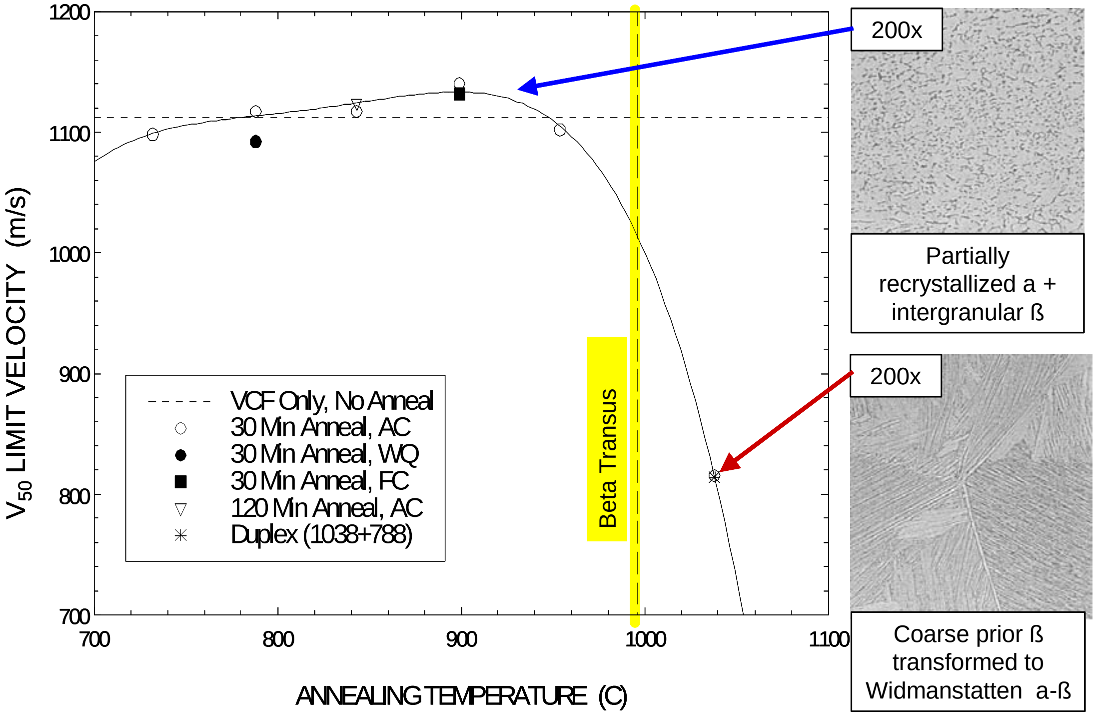


Figure 7. Change in Microstructure for Annealing over the Beta Transus Temperature

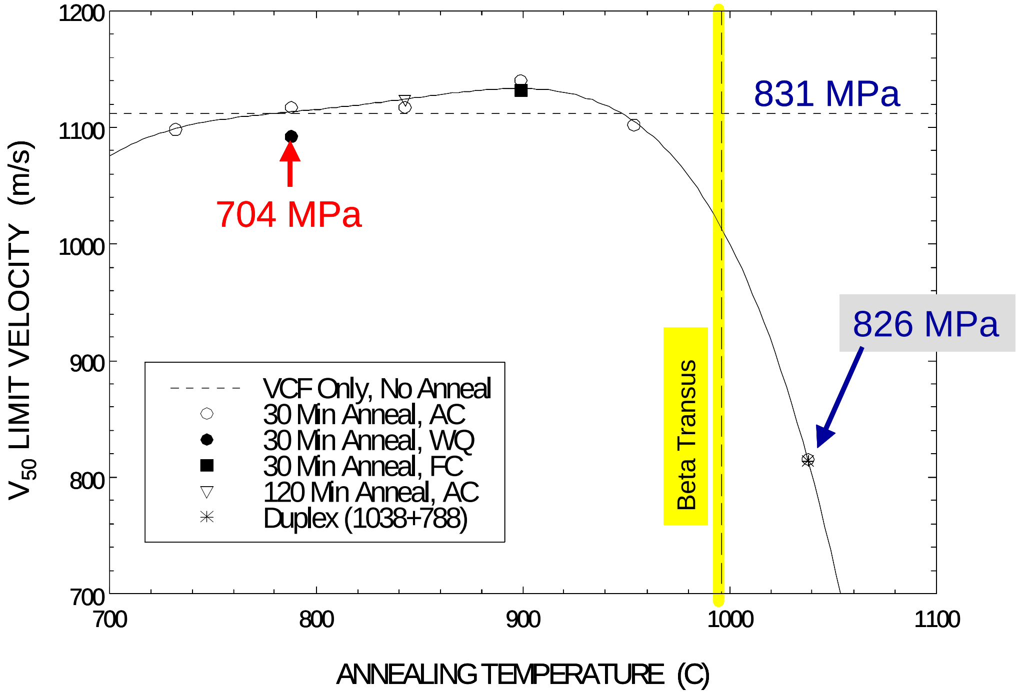


Figure 8. Change in Transverse Yield Strength with Annealing Temperature

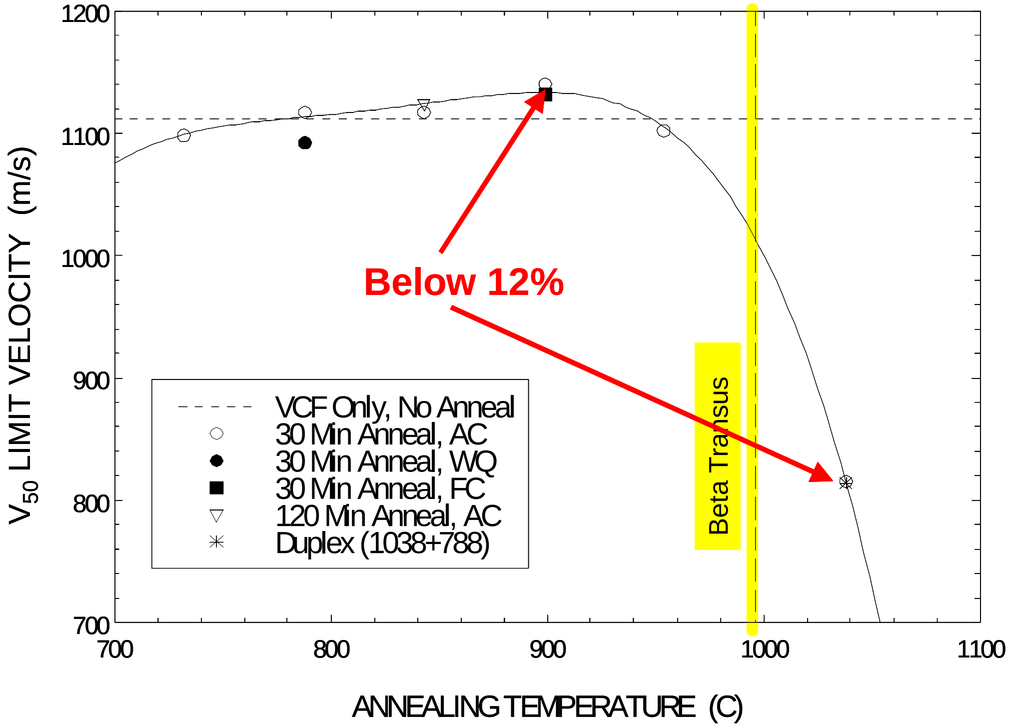


Figure 9. Effect of Transverse Elongation with Annealing Temperature

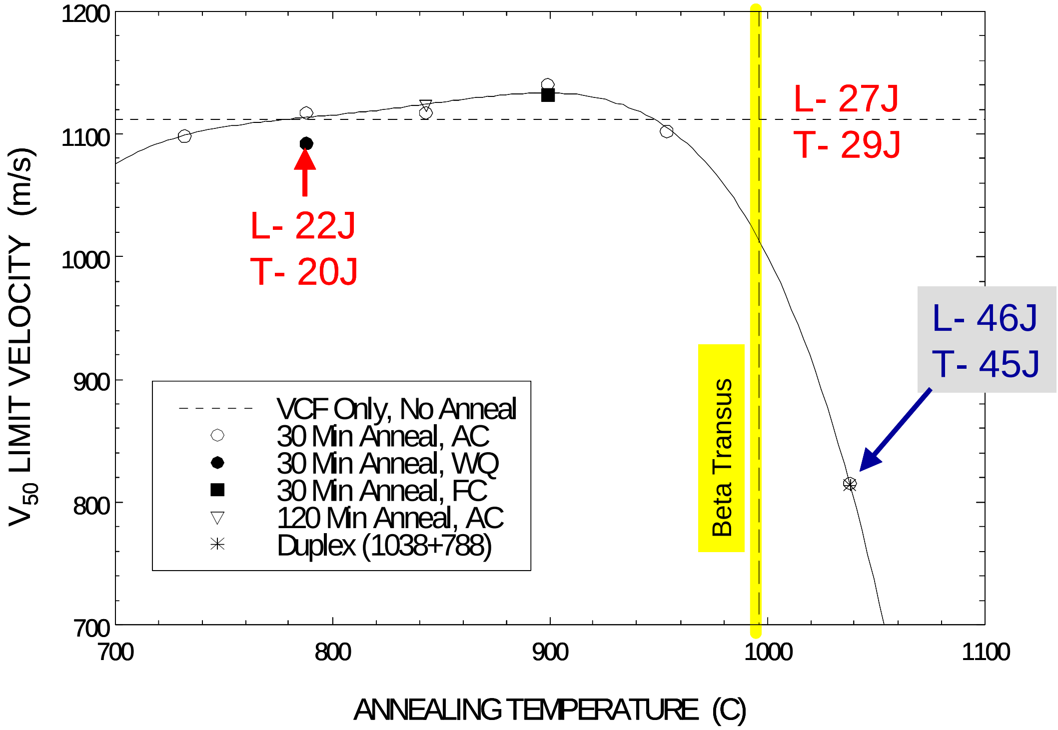


Figure 10. Effect on Charpy Impact Results with Annealing Temperature

## EFFECT OF THERMOMECHANICAL PROCESSING ON BALLISTIC PERFORMA NCE

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.

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$^o$ C (beta) or 954$^o$ 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$^o$ C or 954$^o$ 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$^o$ C for 30 minutes with an air cool (AC); (2) a beta plus alpha-beta anneal at 1,038$^o$ C for 30 minutes with an AC, followed by 788$^o$ C for 30 minutes with an AC; (3) an alpha-beta anneal at 788$^o$ C for 30 minutes with an AC; and (4) a solution treat and age (STA) at 927$^o$ C for 30 minutes with a water quench (WQ), followed by 538$^o$ 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.

$V_{50}$ 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 $V_{50}$ difference for the eleven plate conditions. The required $V_{50}$ 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 $V_{50}$ 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 $V_{50}$ 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 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.

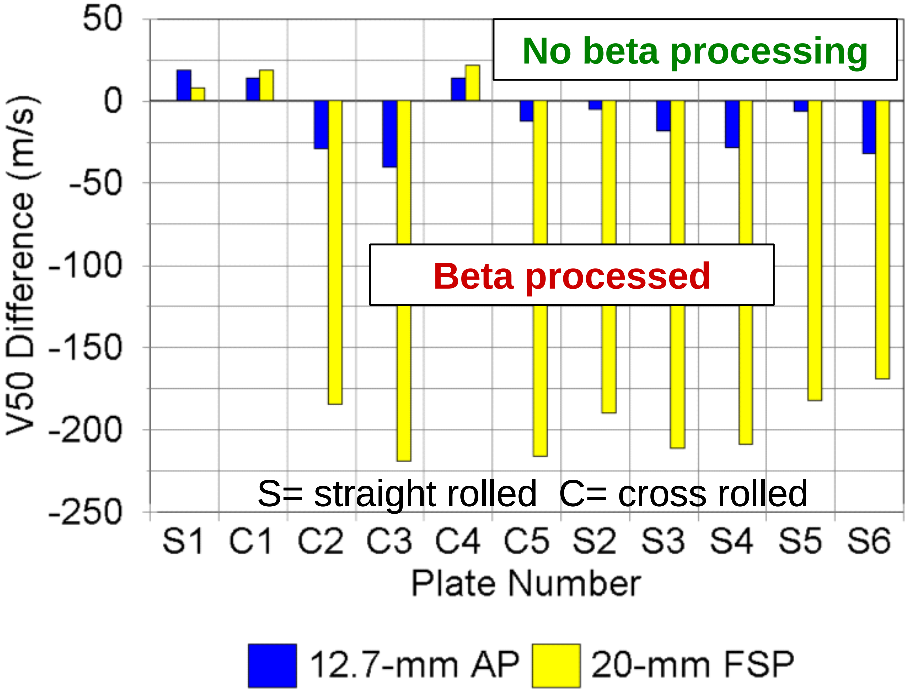


Figure 11. Beta processed Ti-6Al-4V Plate Compared to Alpha-Beta Processed Plate

## 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 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.

### 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.

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. |

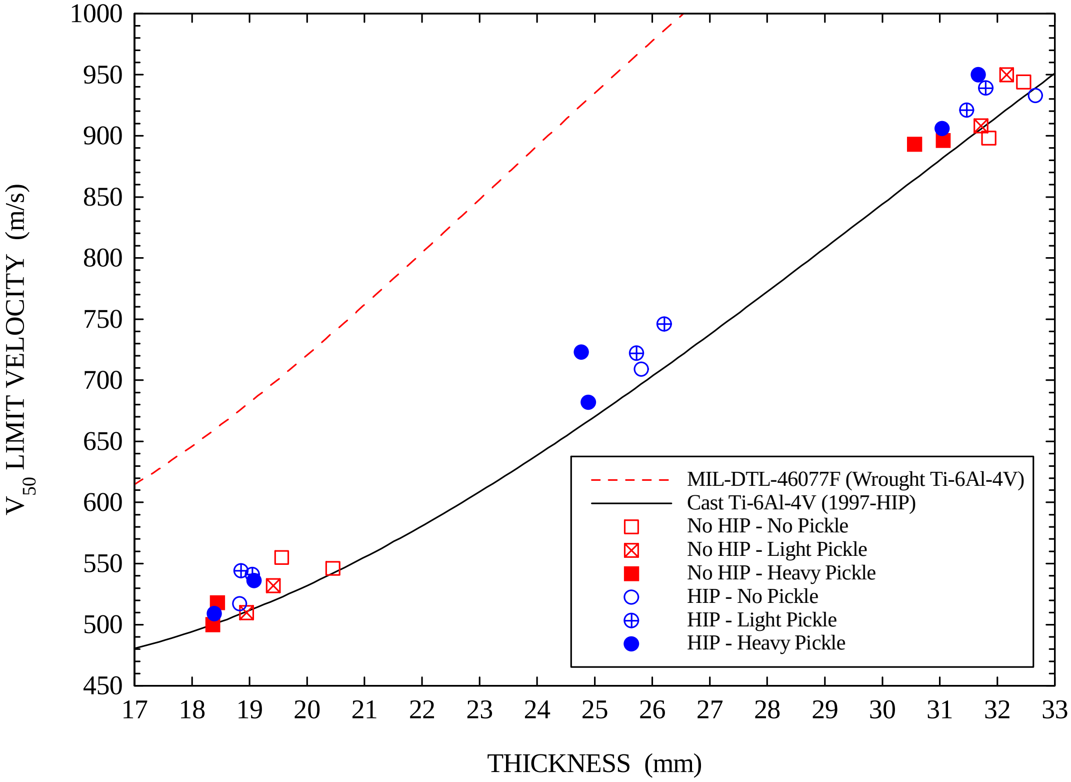


Figure 12. Ballistic Performance of 20mm FSP vs Wrought and Cast Titanium

Figure 13. Titanium Forging of Bradley M2A2 Commanders 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 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.

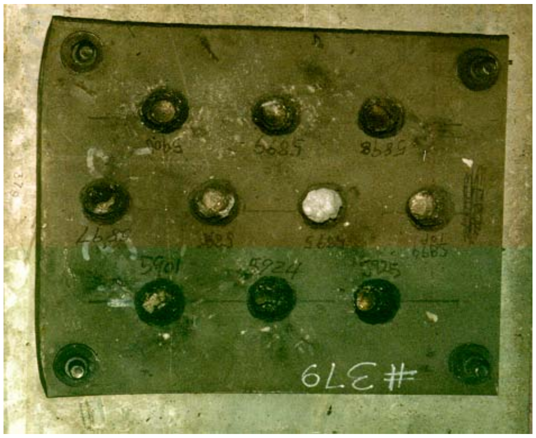


Figure 14. Titanium Wrought Plate Bolted to an Aluminum Rear Plate

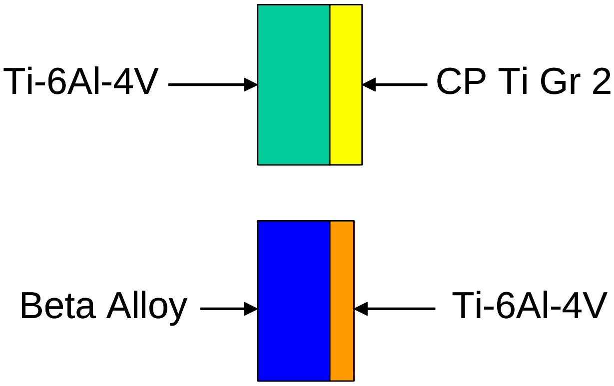


Figure 15. Dual Hard Titanium Concepts

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

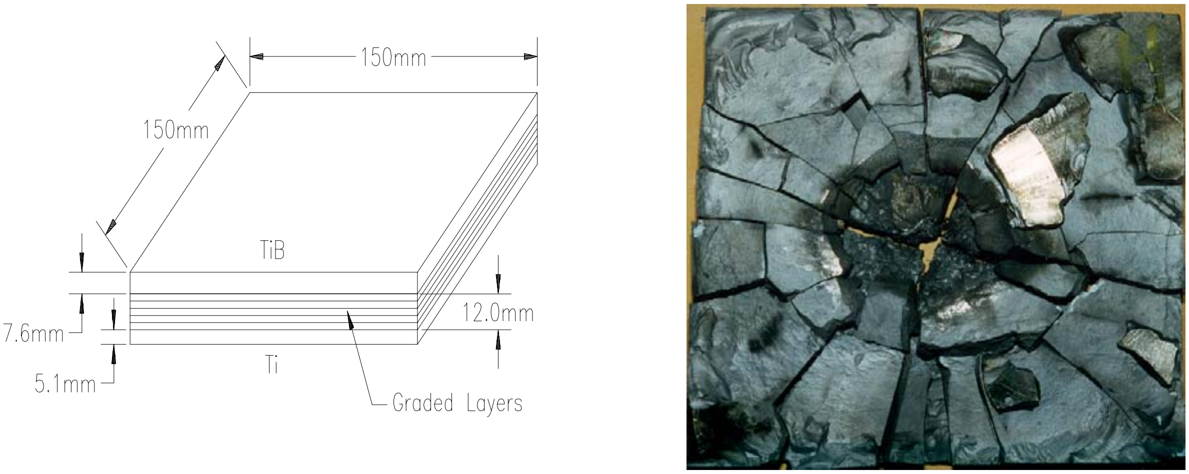


Figure 16. Functionally Graded Titanium Monoboride/Titanium Plate

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.

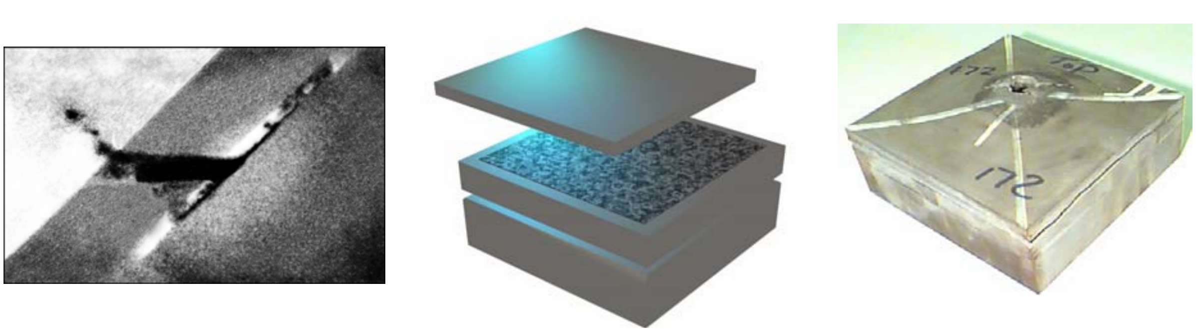


Figure 17. Hot Isostatically Pressed Ceramic in Titanium Matrices

## 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

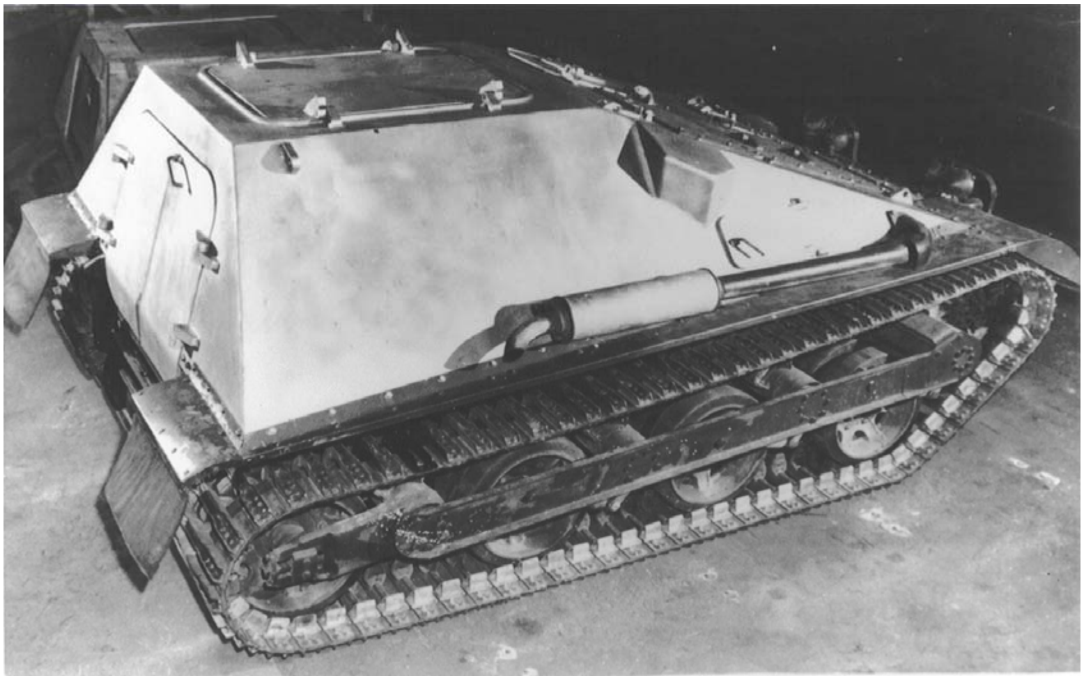


Figure 18. 1960 Detroit Arsenal Titanium Cab on an ONTOS Tracked Vehicle

continued with periodic armor designs, the main drawback to the use of titanium remained the relative cost to other metals. Until very recently, the majority of the structure and armor components for the worlds combat vehicles remained steel based. 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.

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

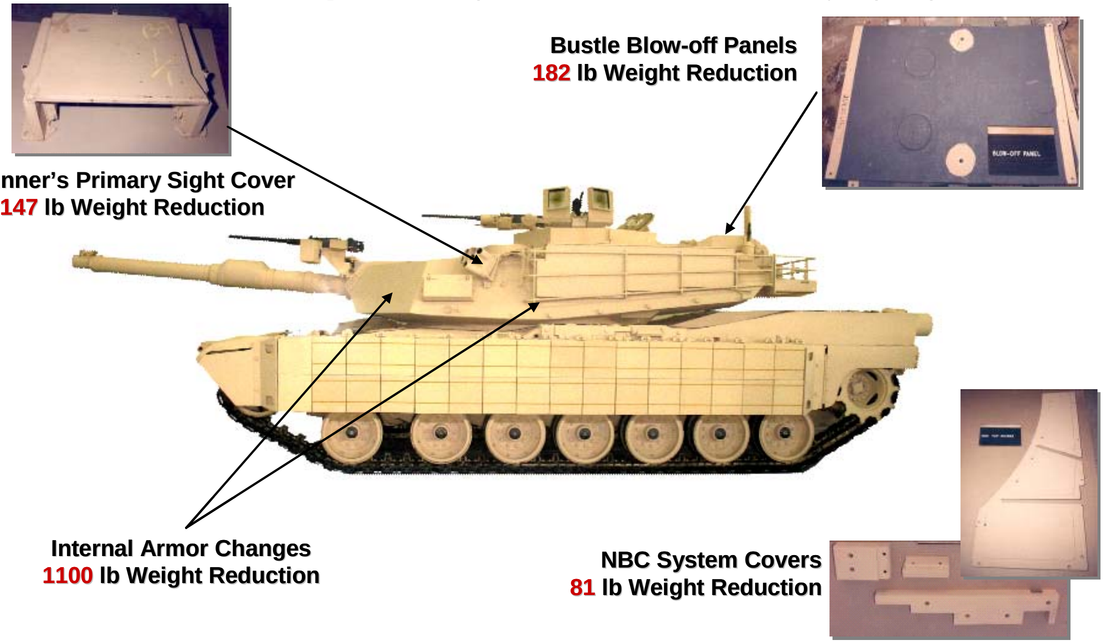


Figure 19. Titanium Weight Reduction Program for M1A2 Abrams Battle Tank

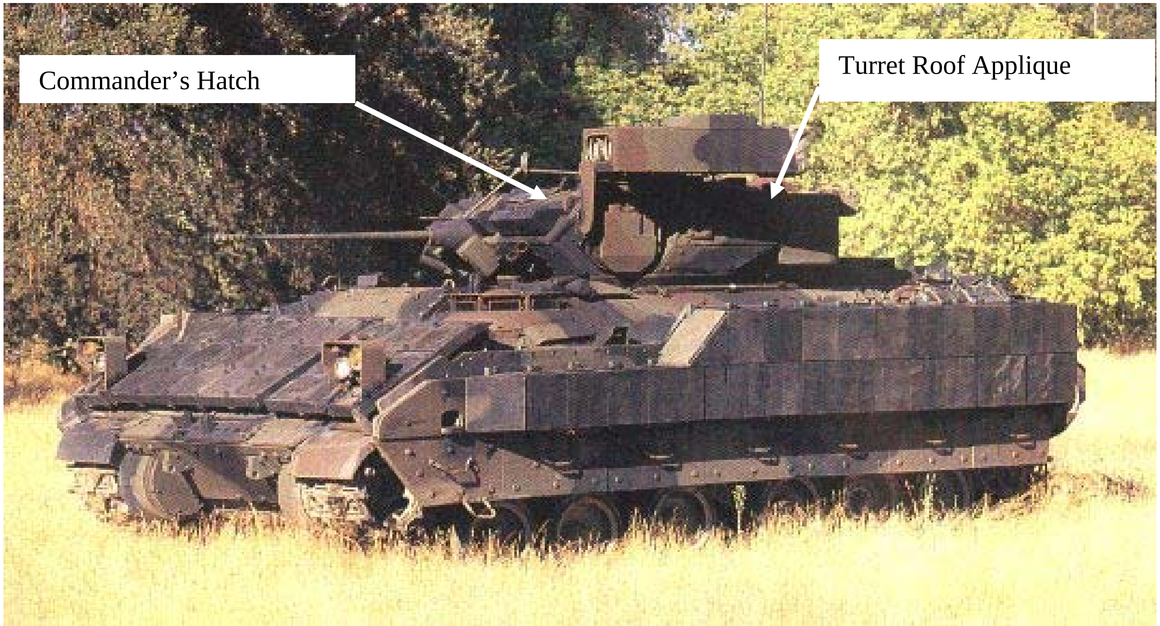


Figure 20. Titanium Commanders Hatch and Roof Applique on M2A2 Bradley Fighting Vehicle

of titanium have been incorporated into design. The drivers hatch is a 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 21. Ultra-light Weight M777A1 Towed Howitzer Utilizes Extensive Titanium

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 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.

Figure 22. BAE Pegasus Titanium Wheeled Prototype

Figure 23. Future Combat Vehicle Titanium Hull Prototype

## REFERENCES

1. Pitler R. and Hurlich A., *Some Mechanical and Ballistic Properties of Titanium and Titanium Alloys*, Report #401/17, Watertown Arsenal Laboratory, March 1950

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, January 1964

3. Donachie M., ed., *Titanium: A Technical Guide*, Metals Park, OH: ASM International, 1989

4. MIL-DTL-46077G, *Armor Plate, Titanium Alloy, Weldable*, 28 September 2007

5. Burkins, M.S., *A Ballistic Evaluation of Ti-6Al-4V vs. Long Rod Penetrators*, ARL-TR-1146, U.S. Army Research Laboratory, July 1996

6. Gooch, W., Burkins, M., Ernst, H.-J., and Wolf, T., *Ballistic Performance of Titanium against Laboratory Penetrators with Aspect-Ratios of 10 or Greater*, Proceedings, 15th International Ballistics Symposium, 1995

7. Gooch, W., Burkins, M., Ernst, H.J., and Wolf, T., *Ballistic Penetration of Titanium Alloy Ti-6Al-4V*, Proceedings of the Lightweight Armour Systems Symposium, The Royal Military College of Science, Shrivenham, Swindon, England, 1995

8. Gooch, W., Burkins, M. and Frank, K., *Ballistic Performance of Titanium Against Laboratory Penetrators*, 1ST Australasian Congress on Applied Mechanics, Melbourne, Australia ,21-23 February 1996

9. Bless, S.J., Gooch, W., Sataphaty, S., Campos, J., and Lee, M., *Penetration Resistance of Titanium and Ultra-Hard Steel at Elevated Velocities*, Proceedings, Hypervelocity Impact Society Symposium, Freiburg, GE, 7-10 Oct 1996

10. Walters, W., Gooch, W., and Burkins, M., *The Penetration Resistance of a Titanium Alloy Against Jets From Tantalum Shaped Charge Liners*, 3rd Joint Classified Ballistics Symposium , San Diego, CA, 1-4 May 2000

11. Jones, T, "Ballistic Performance of Titanium Alloys: Ti-6Al-4V versus Russian Titanium", ARL-CR-0533, U.S. Army Research Laboratory, February 2004

12. Burkins, M., Wells, M., Fanning, J., and Roopchand, B., *The Mechanical and Ballistic Properties of an Electron Beam Single Melt of Ti-6Al-4V Plate*, ARL-MR-515, May 2001

13. Burkins M.S., Love W., and Wood J.R., *Effect of Annealing Temperature on the Ballistic Limit Velocity of Ti-6Al-4V ELI*, Report ARL-MR-359, U.S. Army Research Laboratory, August 1997

14. Burkins M.S., Hansen J., Paige J., and Turner P., *Effect of Thermal Mechanical Processing on the Ballistic Performance of Titanium*, Proceedings, Non-Aerospace Applications of Titanium, Minerals, Metals and Materials Society, San Antonio, TX, ed. By Froes F.H., Allen P.G., and Niinomi M., February 16-19, 1998

15. Burkins M.S., Hansen J., Paige J., and Turner P., *Effect of Thermal Mechanical Processing on the Ballistic Limit Velocity of Extra Low Interstitial Titanium Alloy Ti-6Al-4V*, ARL-MR-486, July 2000

16. Burkins, M.S., Hermann, W., and Kosaka, Y., *A Ballistic Evaluation of Ti-6Al-4V Alloy Castings*, Aeromat 2000, Bellevue (Seattle), 26-29 June 2000.

17. Gooch W., Burkins M. , Palicka R., Rubin J., Ravichandran R., *Development and Ballistic Testing of a Functionally Gradient Ceramic/Metal Applique*, 17th International Ballistics Symposium, Midrand, South Africa, 23-27 March 1998

18. Hauver, G., Rapacki, Jr., E., Netherwood, P., and Benck, R., *Interface Defeat of Long-Rod Projectiles by Ceramic Armor*, ARL-TR-3590, September 2005

19. Gooch, W., *Overview of the Development of Ceramic Armor Technology: Past, Present and in the Future*, 30th International Conference on Advanced Ceramics and Composites, Cocoa Beach, Fl, 22-27 January 2006.

20. Figure provided Courtesy of PEO CS&CSS, PM Abrams, Warren, MI

21. Wells, M., Roopchand, B., Montgomery, J., and Gooch, W., *Titanium Applications and R&D for Army Ground Systems*, Proceedings of 1998 TMS Annual Meeting, San Antonio, TX, 16-19 Feb 1998,

22. Website, Army-Technology.com

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

RDECOM

# THE DESIGN AND APPLICATION OF TITANIUM ALLOYS FOR US ARMY PLATFORMS

MILITARY PANEL

OCTOBER 9, 2007

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

**William. A. Gooch**
**U.S. Army Research Laboratory**
**Weapons and Materials Research Directorate**
**Aberdeen Proving Ground, MD 21005-5066**

**THIS PRSENTATION IS UNCLASSIFED/PUBLIC DOMAIN**

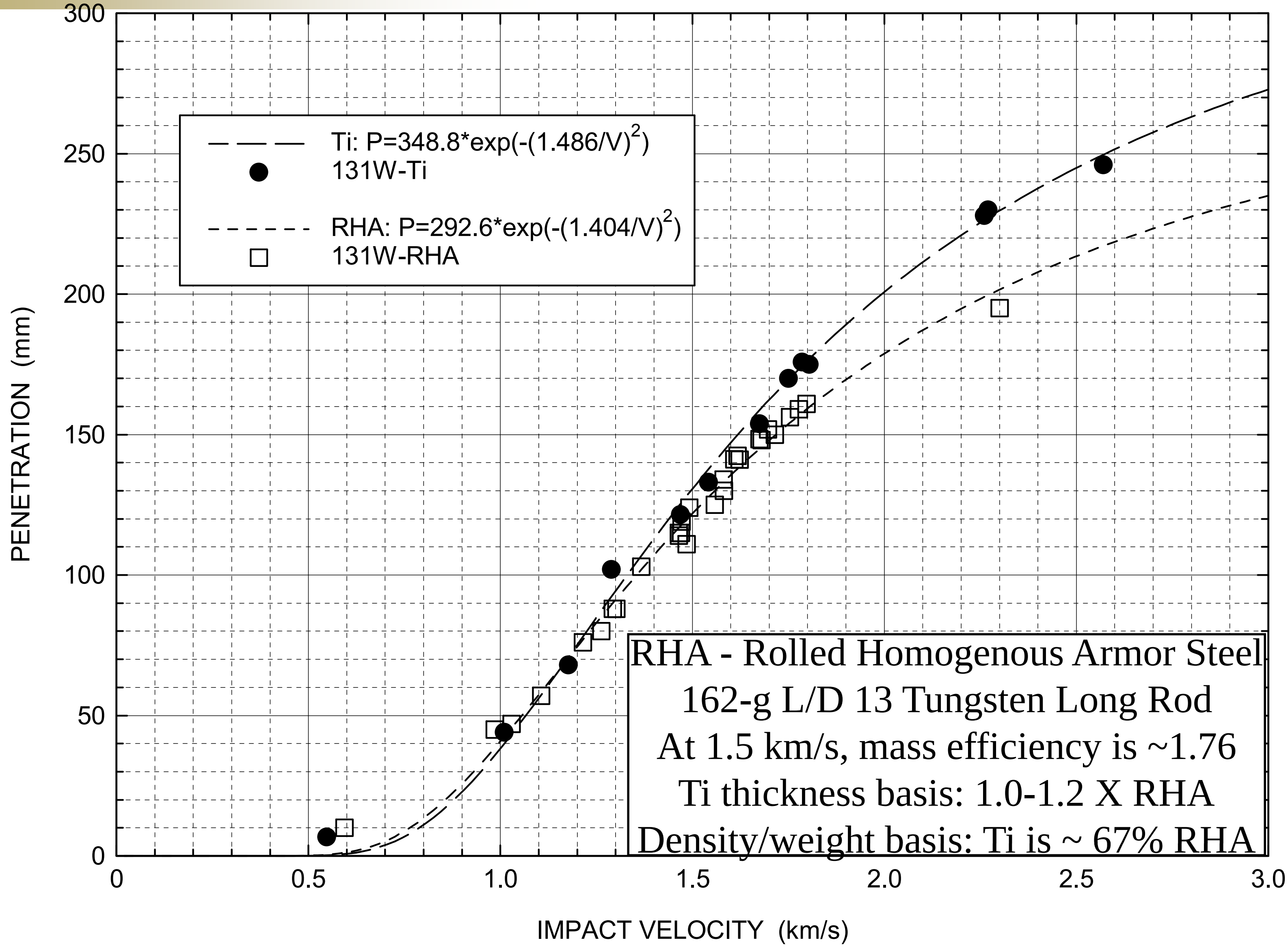
# Introduction

- 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-A-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-A-46077G Classes 1-4

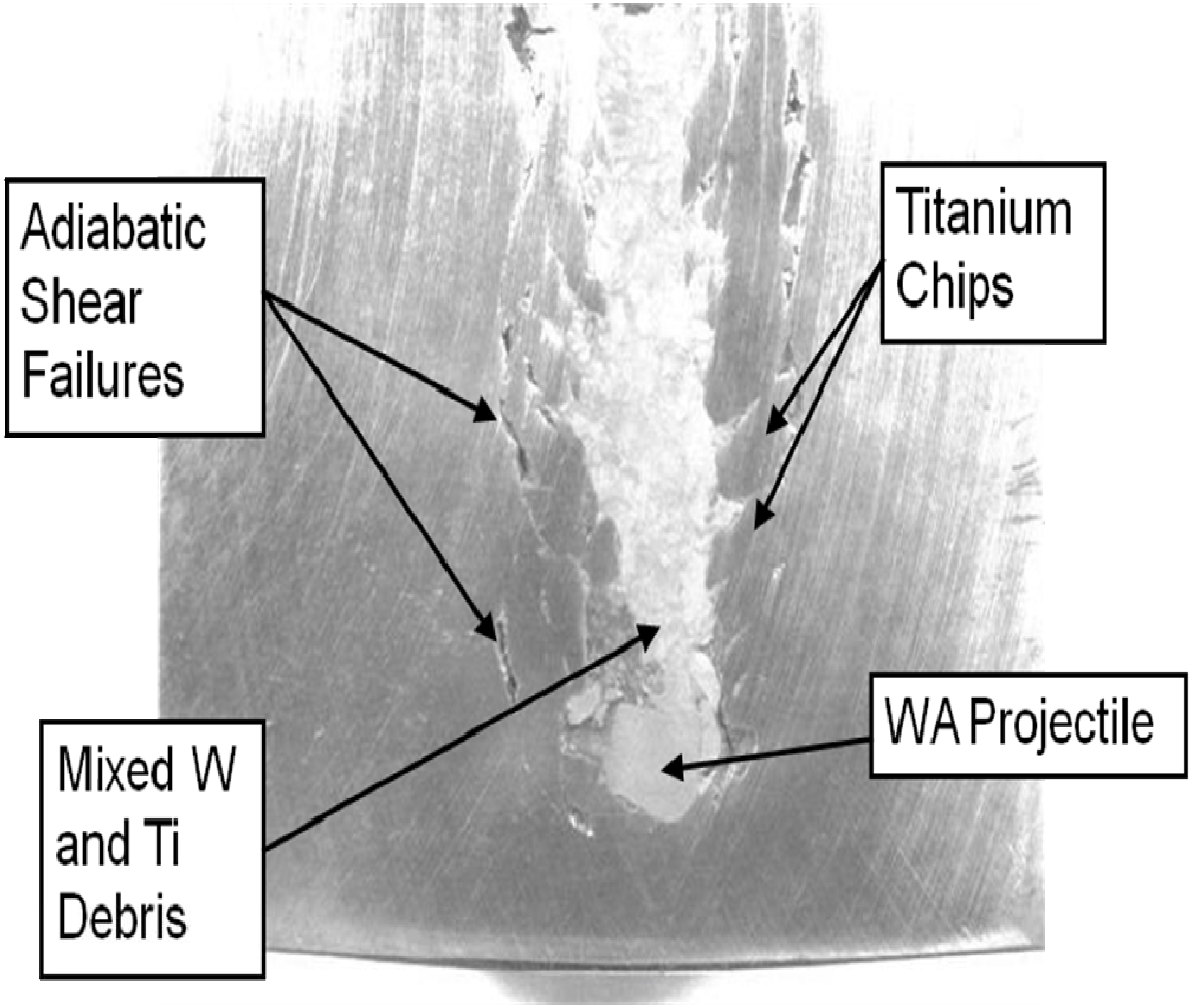
| | Chemistry | Max. $O_2$ Content | Comments |
|---|---|---|---|
| Class 1 | 6AL- 4V | 0.14% | ***ELI-***<br>10% Elongation Min. |
| Class 2 | 6AL- 4V | 0.20% | ***Common Armor***<br>6% Elongation Min. |
| Class 3 | 6AL- 4V | 0.30% | ***High Scrap Content***<br>Weld & cold temp issues |
| Class 4 | Not Limited | 0.30% | ***For future developments*** |

# Ballistic Performance of RHA and Titanium



RHA - Rolled Homogenous Armor Steel
162-g L/D 13 Tungsten Long Rod
At 1.5 km/s, mass efficiency is ~1.76
Ti thickness basis: 1.0-1.2 X RHA
Density/weight basis: Ti is ~ 67% RHA

# Deep Penetration into Titanium Showing Adiabatic Shear Bands



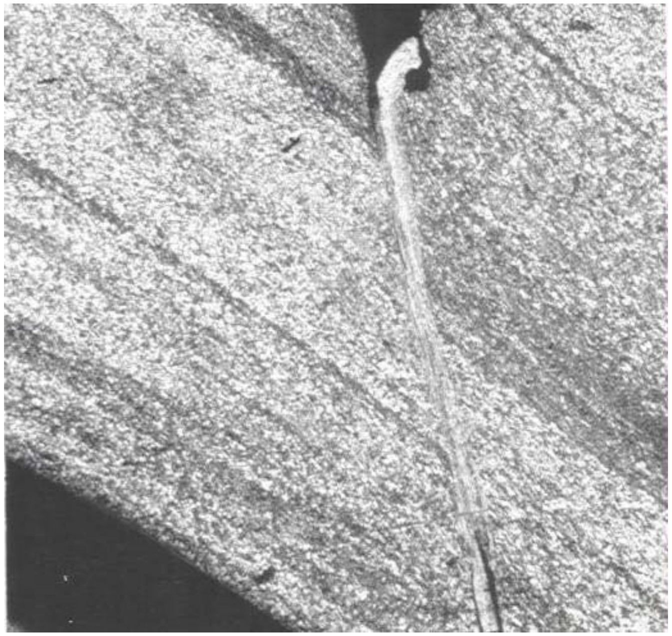
# Adiabatic Shear Bands in Titanium

Strain causes localized heating

Heat cannot dissipate

Material softens

Additional strain in soft areas



# Spall Plug Breakout of Titanium

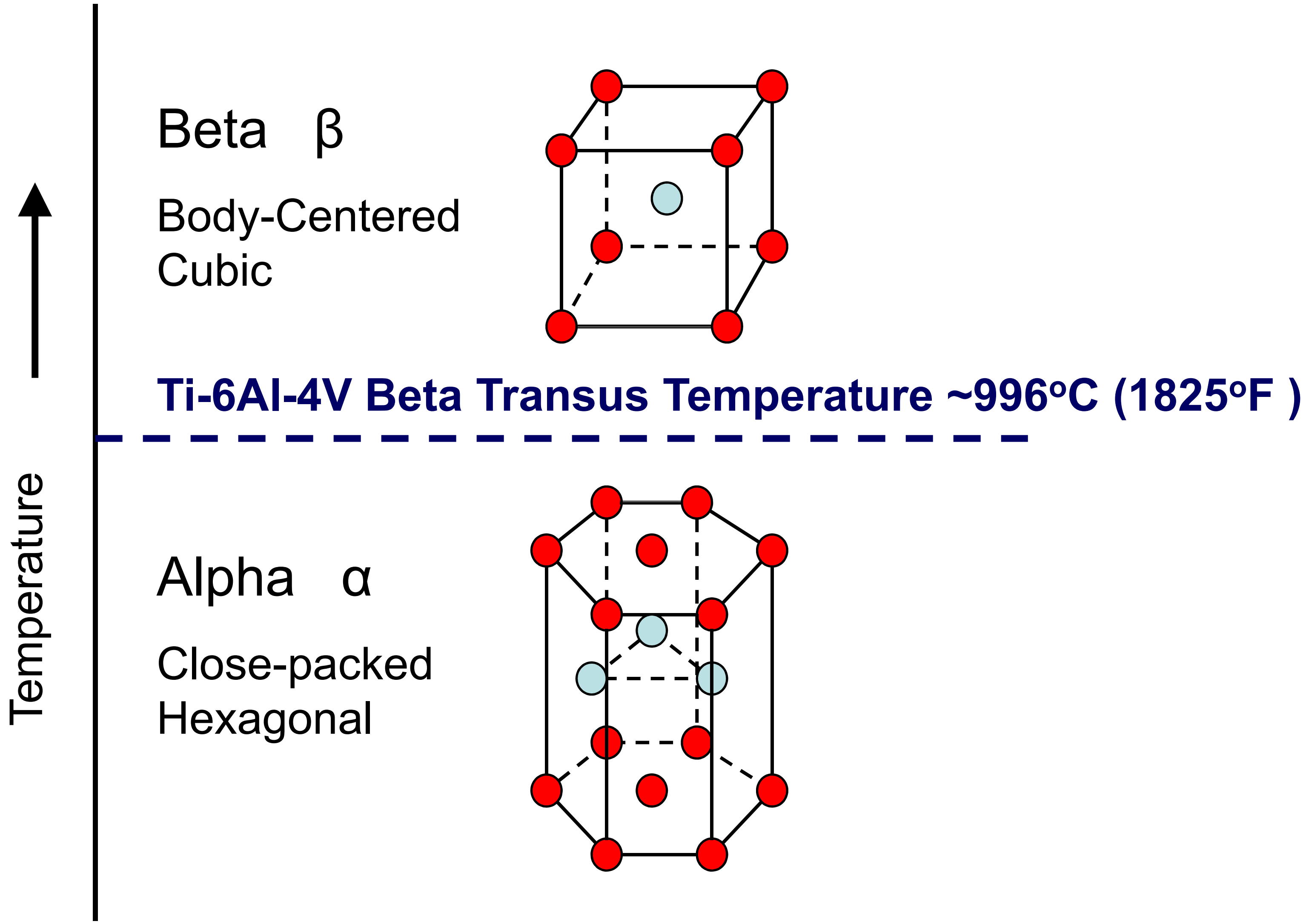
SPALL RING BREAKOUT

SHEAR BANDS AND DELAMINATION

PENETRATOR CHANNEL

SHEAR BANDS AND DELAMINATION

# Beta Transus for Ti-6Al-4V and Processing History



Temperature

Beta β

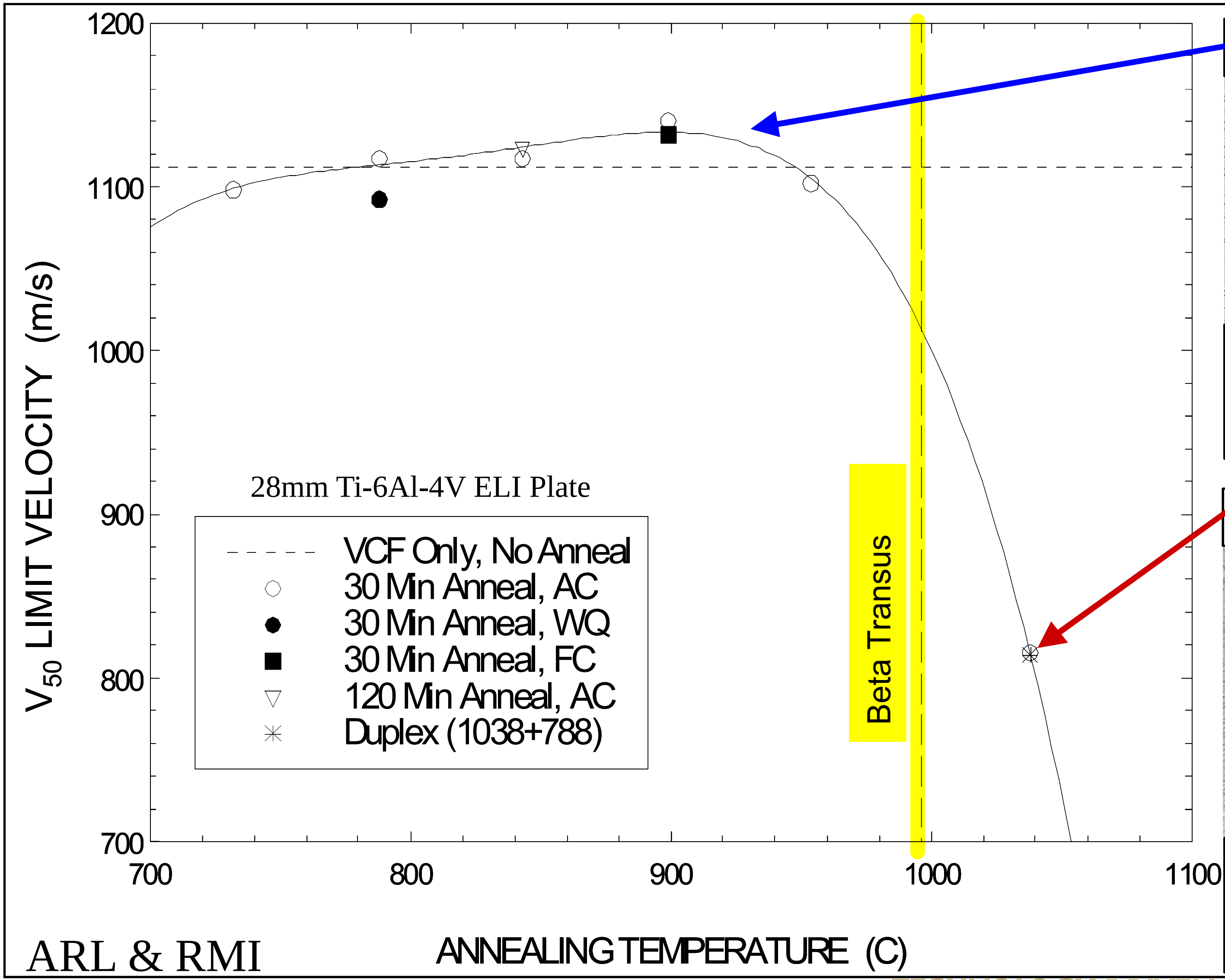
Body-Centered
Cubic

**Ti-6Al-4V Beta Transus Temperature ~996°C (1825°F )**

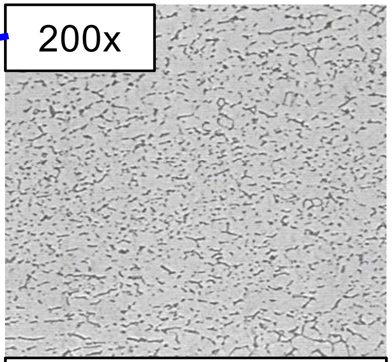
Alpha α

Close-packed
Hexagonal

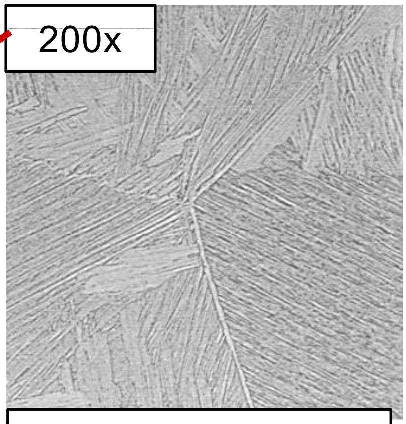
# Effect of Annealing Temperature on Microstructure and Ballistic Performance



ARL & RMI

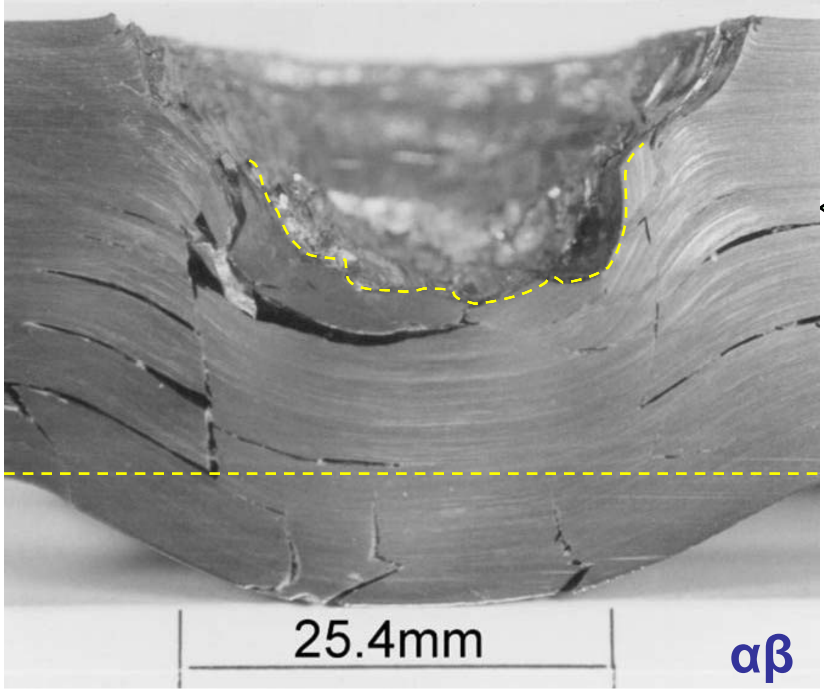


Partially recrystallized a + intergranular ß



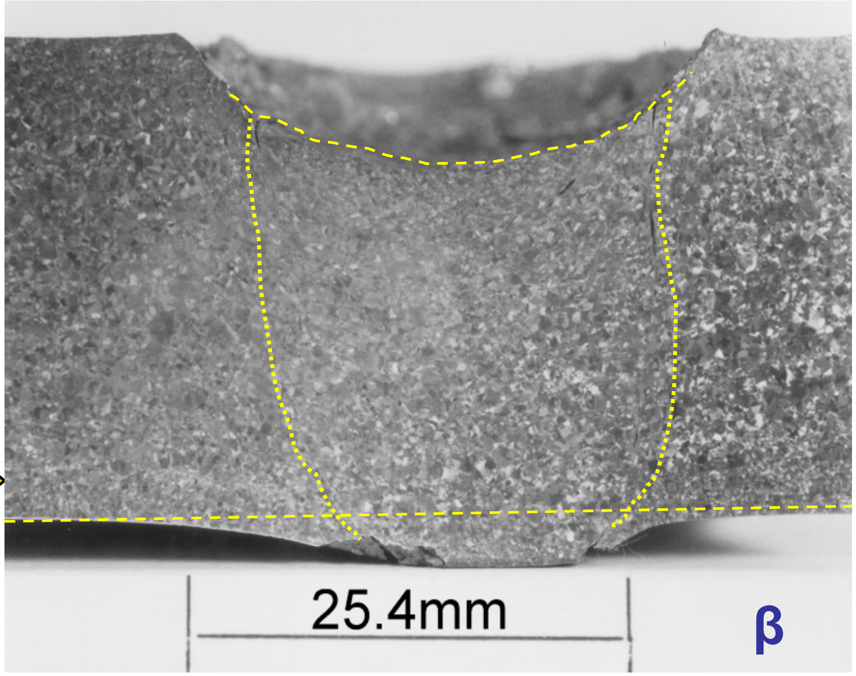
Coarse prior ß transformed to Widmanstatten a-ß

# Failure Analysis of 20mm Fragment Simulating Projectile Impact



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

Failure by low-energy plugging

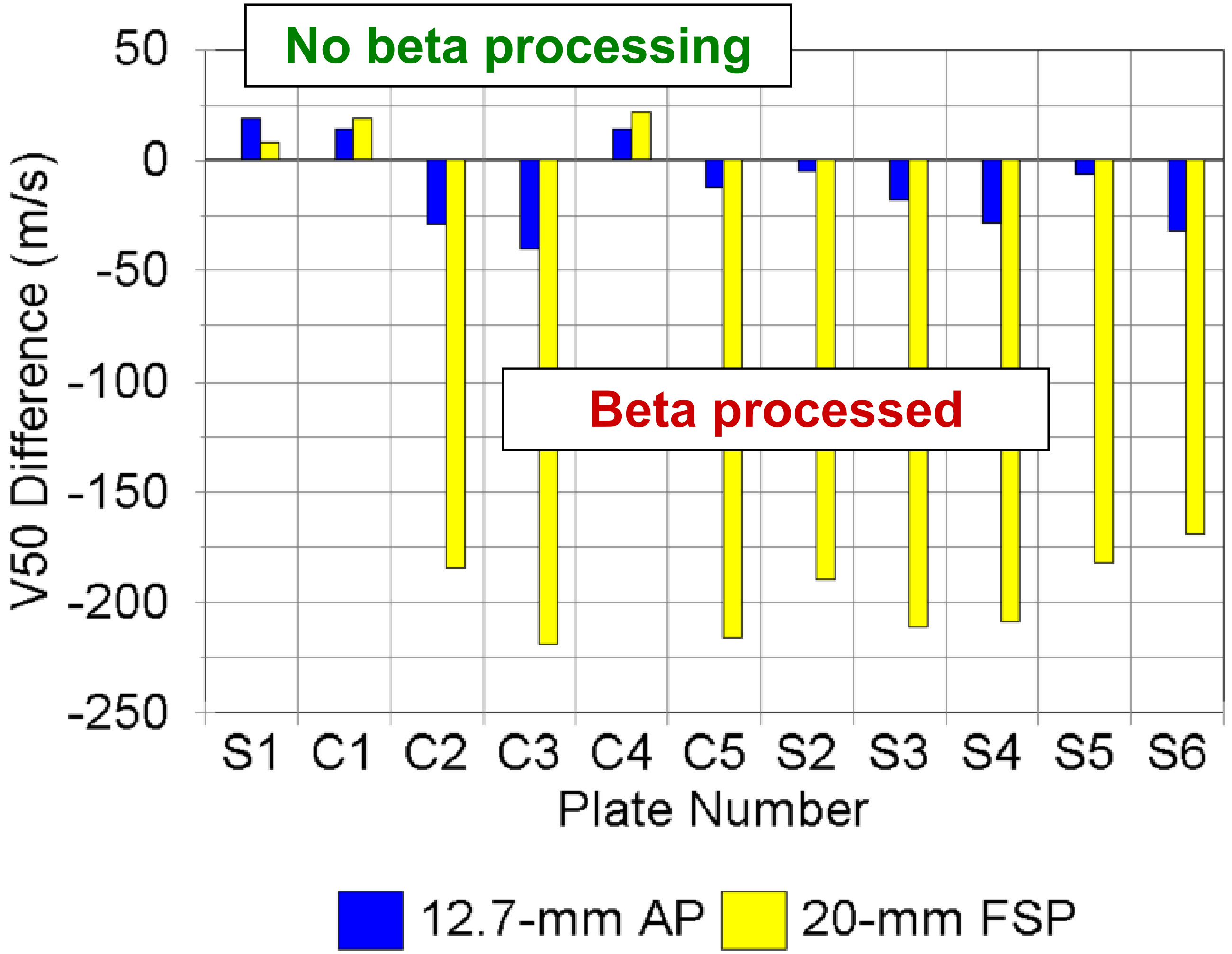


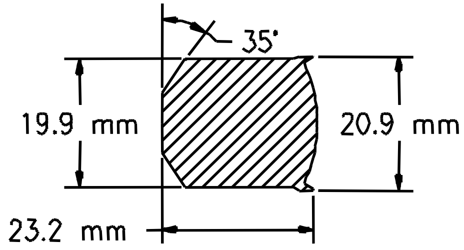
# Bottom Line

**Low strain rate mechanical properties provide no guarantee for ballistic performance!**

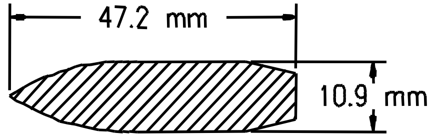
**That's why military armor specifications were developed.**

# Ti-6Al-4V Thermomechanical Processing (127mm to 25.5mm)





20–mm FSP
Steel, Rc 29–31
Mass: 53.8 g



12.7–mm AP M2 Core
Steel, Rc 60–65
Mass: 25.4 g

**V50 Difference= Test V50 – Required V50**

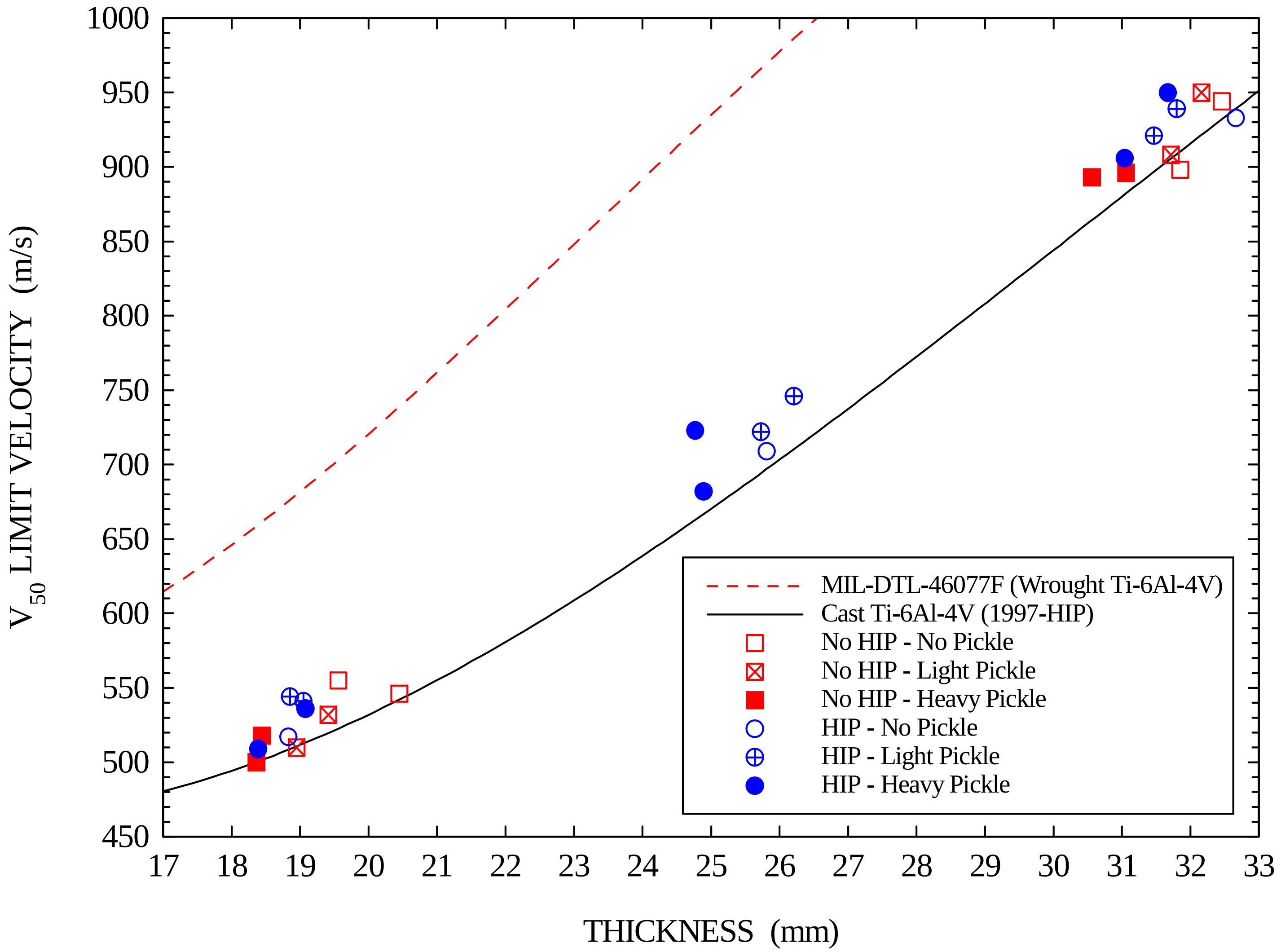
# Beta Processing Concerns

- 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.**

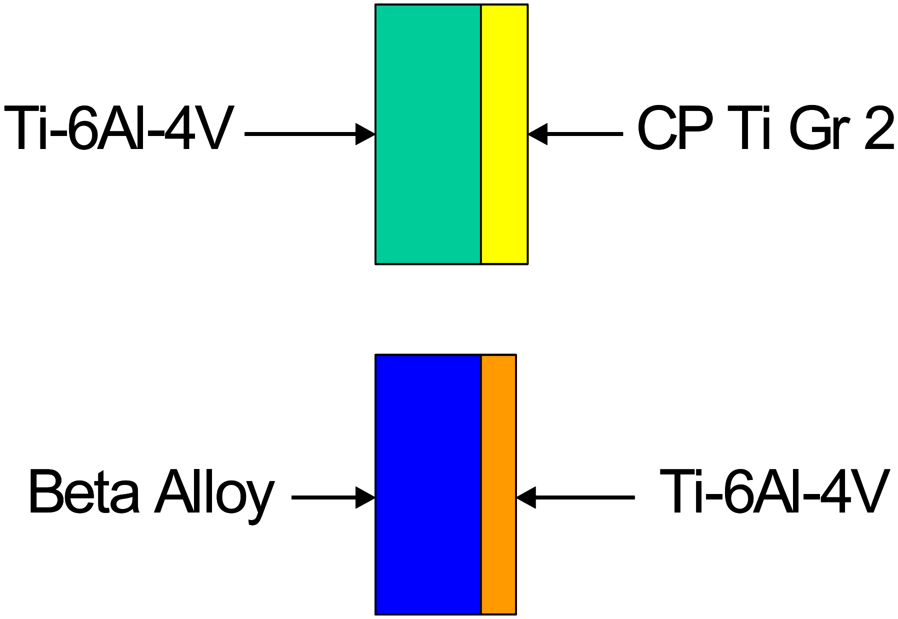
# Ballistic Performance of 20mm FSP vs Wrought and Cast Titanium



ARL, GD & ATI

# Titanium Laminates

Titanium Wrought Plate Bolted to an Aluminum Rear Plate

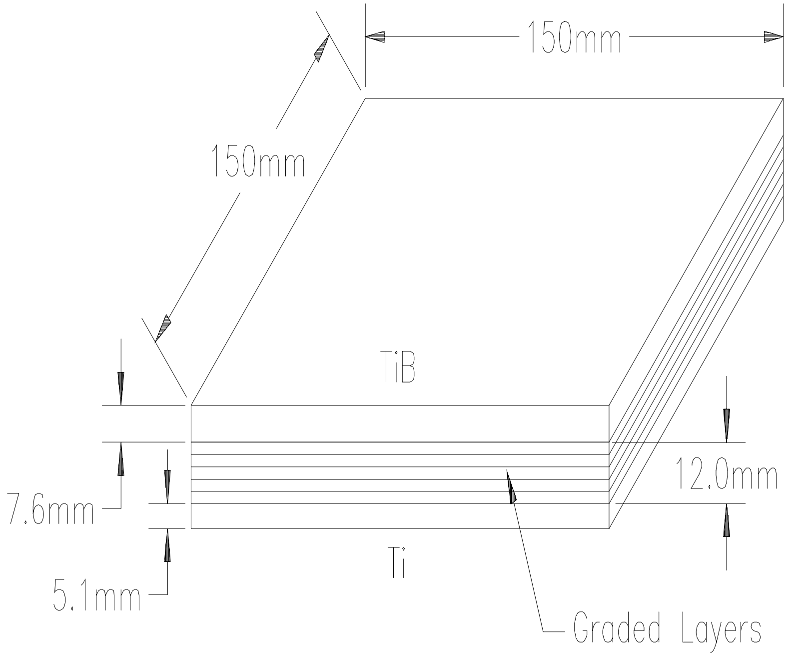


Ti-6Al-4V → ← CP Ti Gr 2

Beta Alloy → ← Ti-6Al-4V

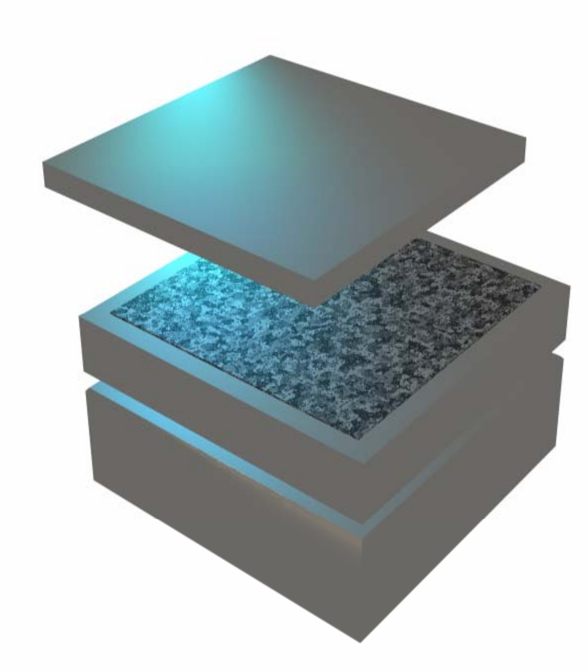
Dual Hard Titanium Concepts

# Functionally Graded Titanium Monoboride/Titanium Plate

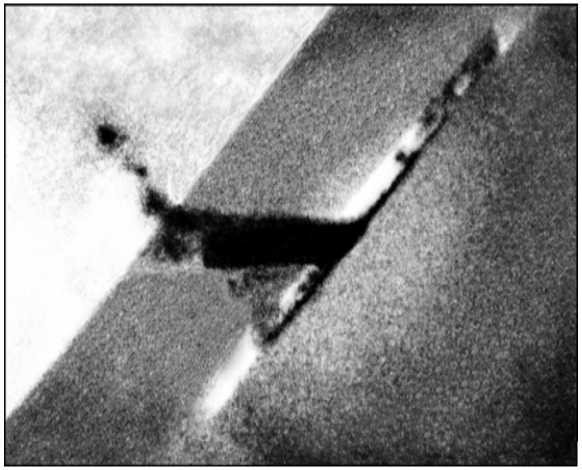


ARL & BAE

# Hot Isostatically Pressed Ceramic in Titanium Matrices



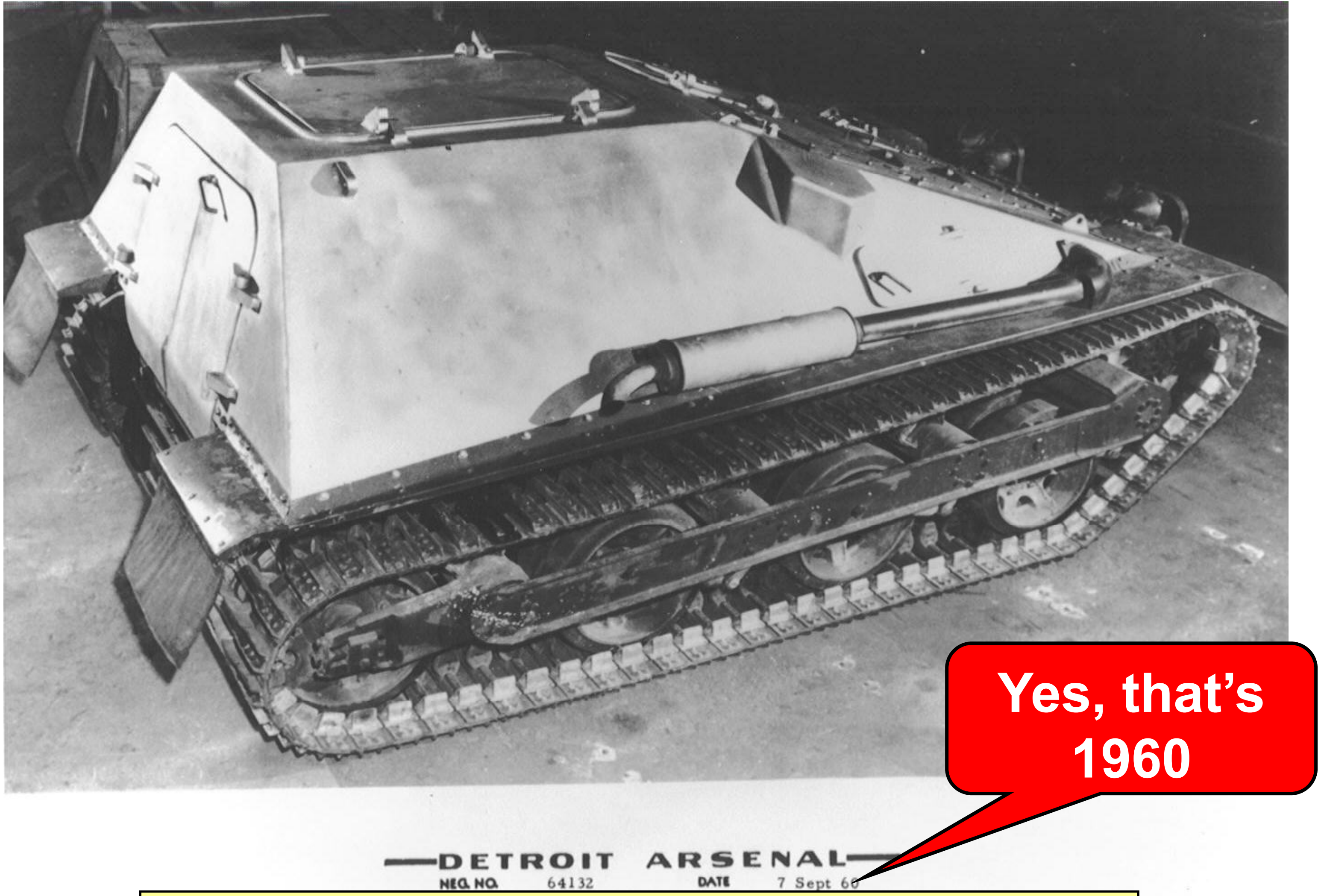
Titanium/Ceramic Preform before HIP



Dwell on Ceramic by Long Rod Penetrator

Post Impact Condition

# Titanium Welding



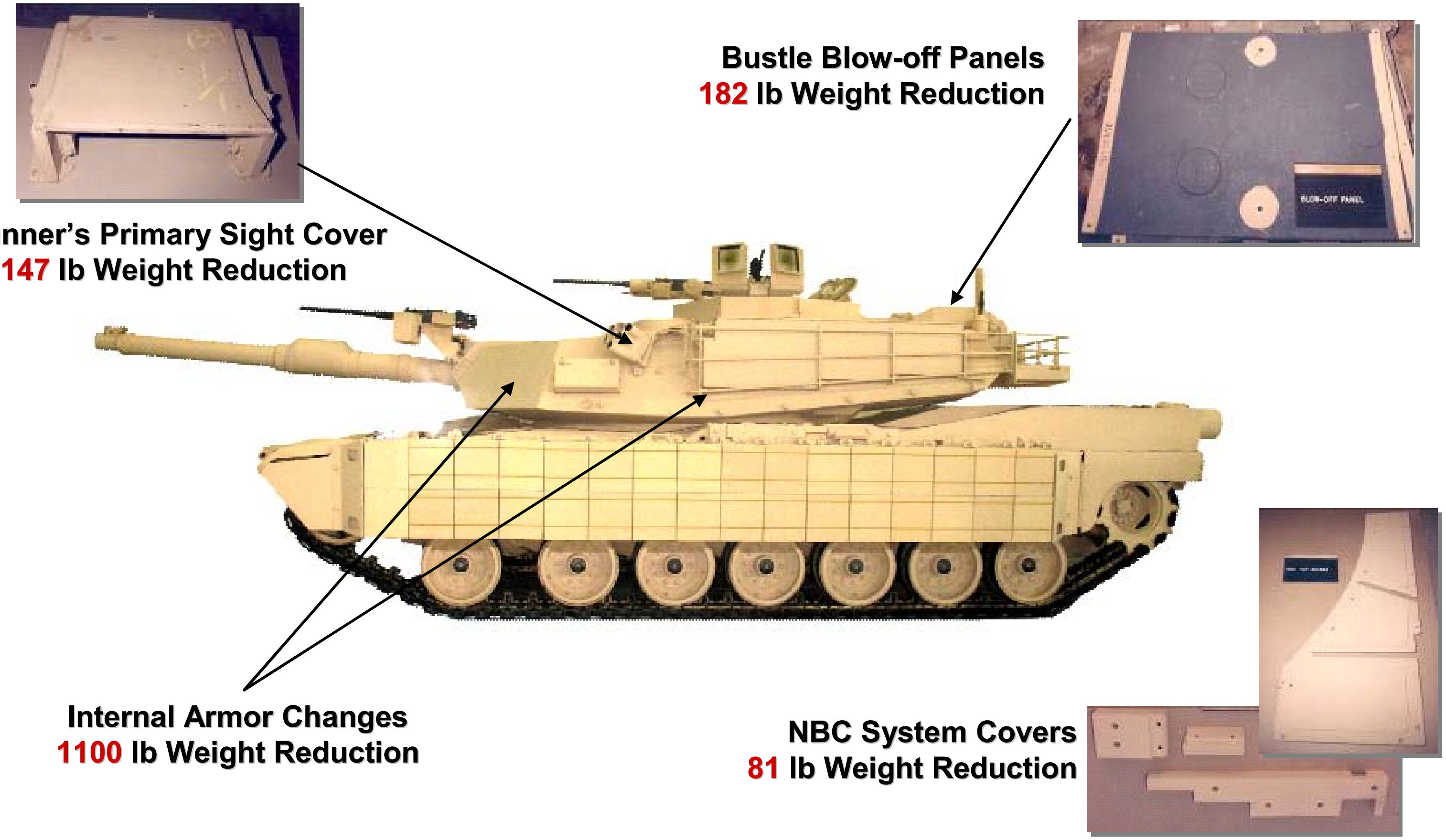
**Yes, that's 1960**

Titanium Cab on ONTOS Vehicle

# Ballistic Welds

- **Ballistic Welds always perform worse than parent metal**
- **Current MIL-A-46077G titanium is weldable by definition, however…..**
- **Titanium needs a standard to insure weldments withstand ballistic shock**
  - **Similar to MIL-STD-1941 for steel and MIL-STD-1946 for aluminum**
  - **Non-penetrating impact by large, blunt projectile traveling at low velocity**

# Titanium Weight Reduction Program for M1A2 Abrams Battle Tank



**Bustle Blow-off Panels**
**182 lb Weight Reduction**

**Gunner's Primary Sight Cover**
**147 lb Weight Reduction**

**Internal Armor Changes**
**1100 lb Weight Reduction**

**NBC System Covers**
**81 lb Weight Reduction**

GDLS >1500 lbs weight savings

# Applications

## Titanium Commander Hatch and Roof Applique on M2A2 Bradley Fighting Vehicle

# Applications

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

>7000lbs savings over M198

# BAE Pegasus Titanium Wheeled Prototype

BAE

# Future Combat Vehicle Titanium Hull Prototype

RL & BAE

# Conclusions

- This presentation has provided a cursory overview of the technical investigation of titanium for military ground applications
- 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
- The current Military Specification MIL-A-46077G increases the thicknesses range of titanium alloys as well as allowing Class 3 and 4 alloys that offer lower cost through increased oxygen levels, greater scrap content and advanced processing technology
- The importance of processing temperatures has been emphasized in many slides, particularly processing over the Beta Transus of Ti-6Al-4V
- The presentation has ended with a few of current and proposed future applications of titanium in military ground vehicles and the requirements to reduce combat weights drives applications towards the lower density metals that have excellent ballistic properties

Thank you