The Design and Application of Titanium Alloys to U.S. Army Platforms -2010

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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 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 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 past and current applications of titanium on US Army platforms and augments previous presentations given in this forum in 2007, 2008 and 2009.

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^{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 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.

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 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

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

	Chemistry	Max. O_2 Content	Comments
Class 1	6AL-4V	0.14%	***ELI-*** 10% Elongation Min.
Class 2	6AL-4V	0.20%	***Common Armor*** 6% Elongation Min.
Class 3	6AL-4V	0.30%	***High Scrap Content*** 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.

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

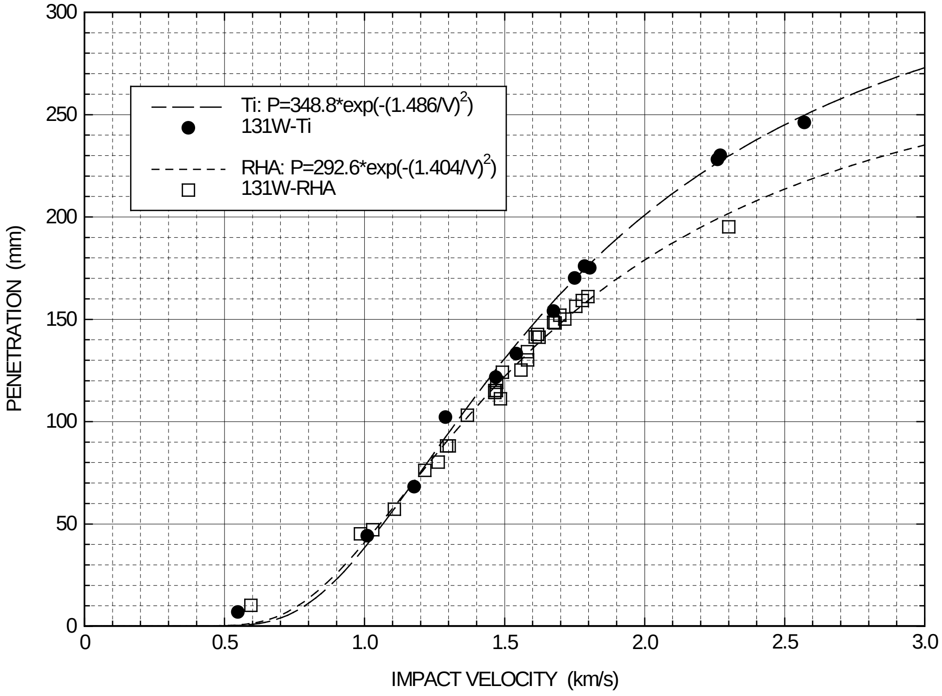


Figure 1. Penetration of a Tungsten Long Rod Penetrator into RHA and Titanium

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 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 spall 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.

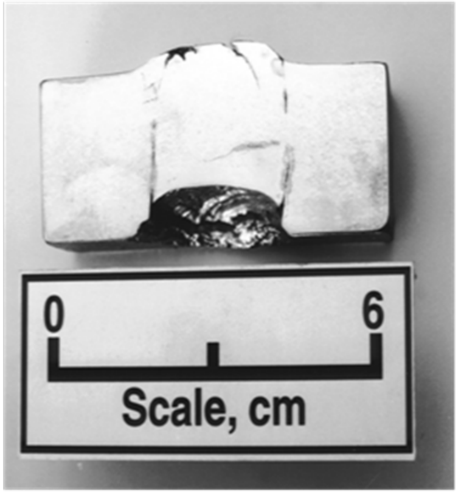


Figure 2. Cross-section of Impact Crater from 20-mm FSP for Beta Processed Plate

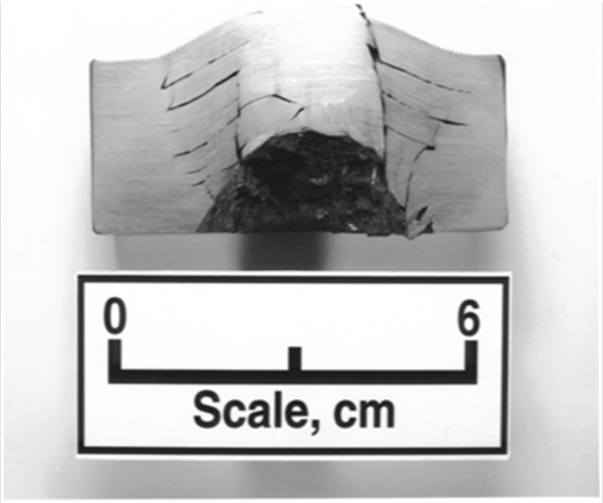


Figure 3. Cross-section of Impact Crater from 20-mm FSP for Alpha-Beta-Processed Plate

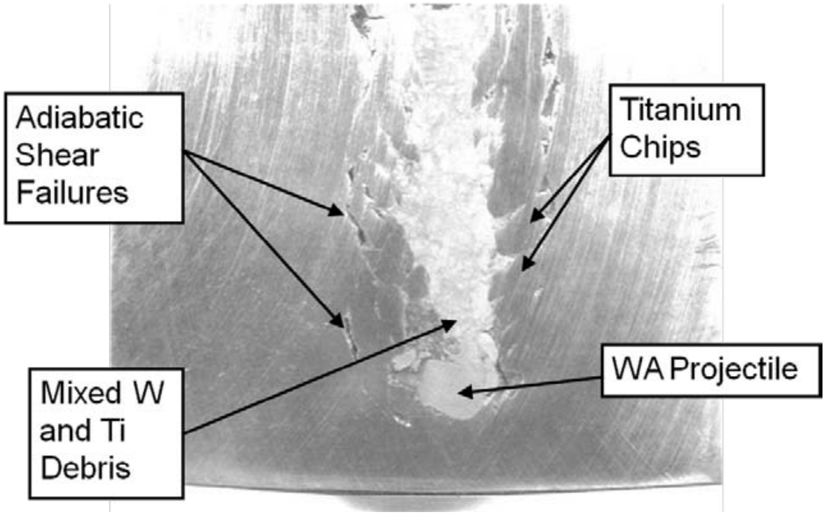


Figure 4. Deep Penetration of a Tungsten Long Rod Penetrator into Titanium showing Adiabatic Shear Bands

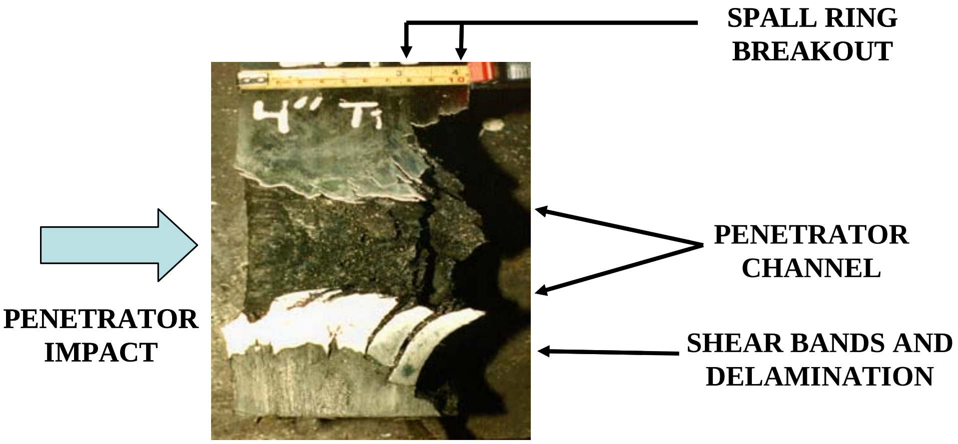


Figure 5. Spall Plug Breakout of a 100mm (4.0”) Titanium Plate after Perforation by a Long Rod Penetrator

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.

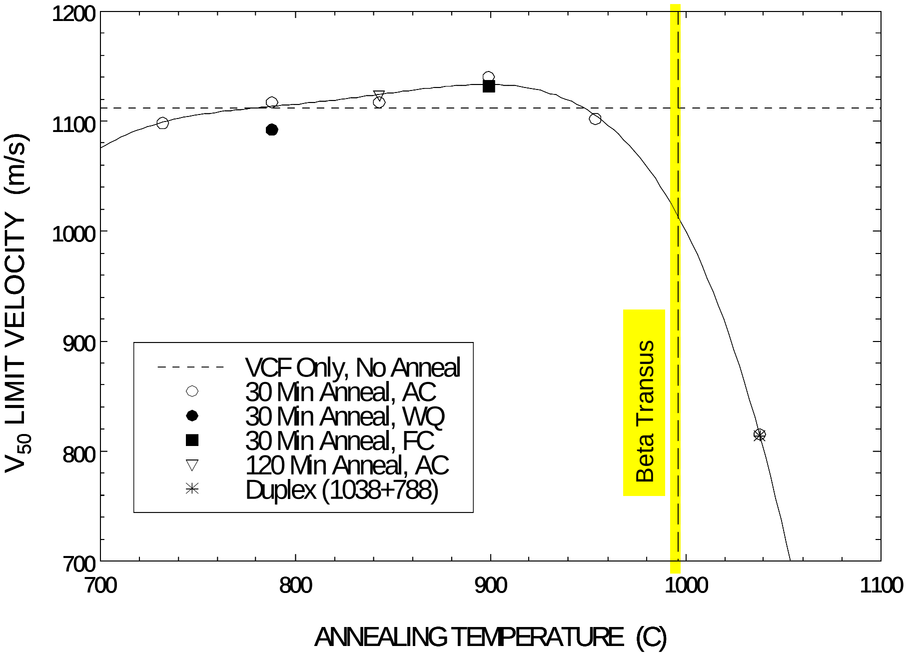


Figure 6. Effect of Annealing Temperature on Ballistic Performance

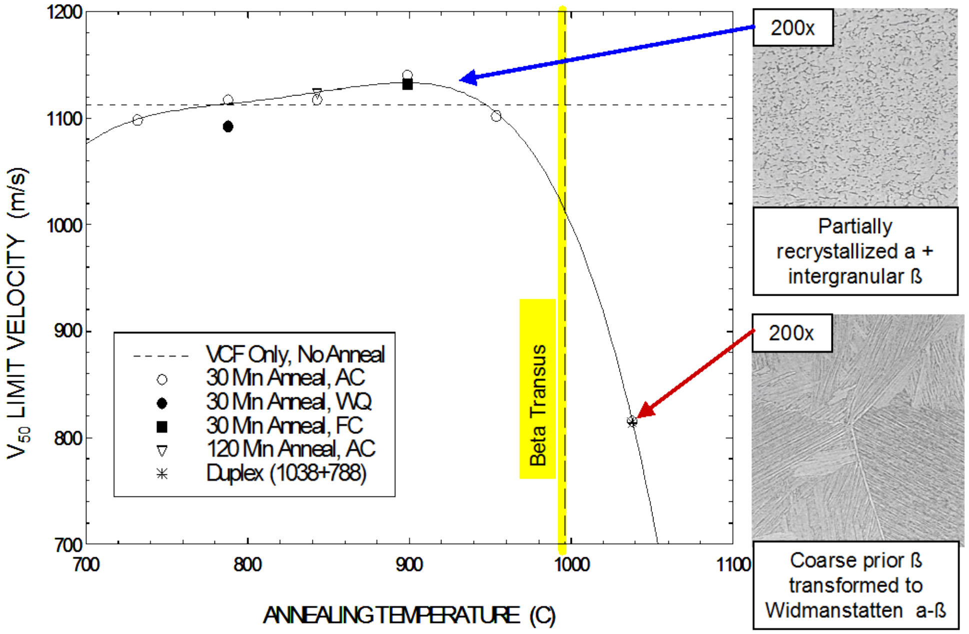


Figure 7. Change in Microstructure for Annealing over the Beta Transus Temperature

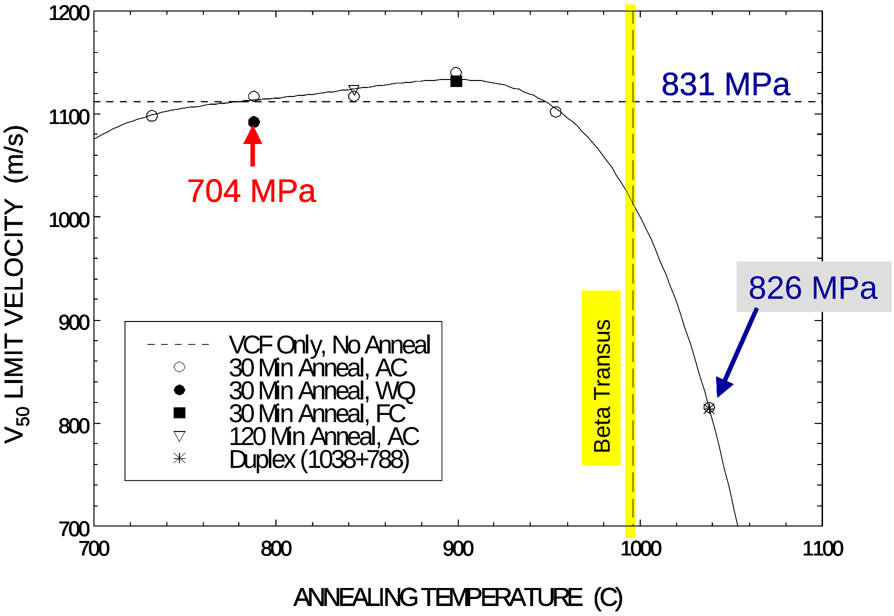


Figure 8. Change in Transverse Yield Strength with Annealing Temperature

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.

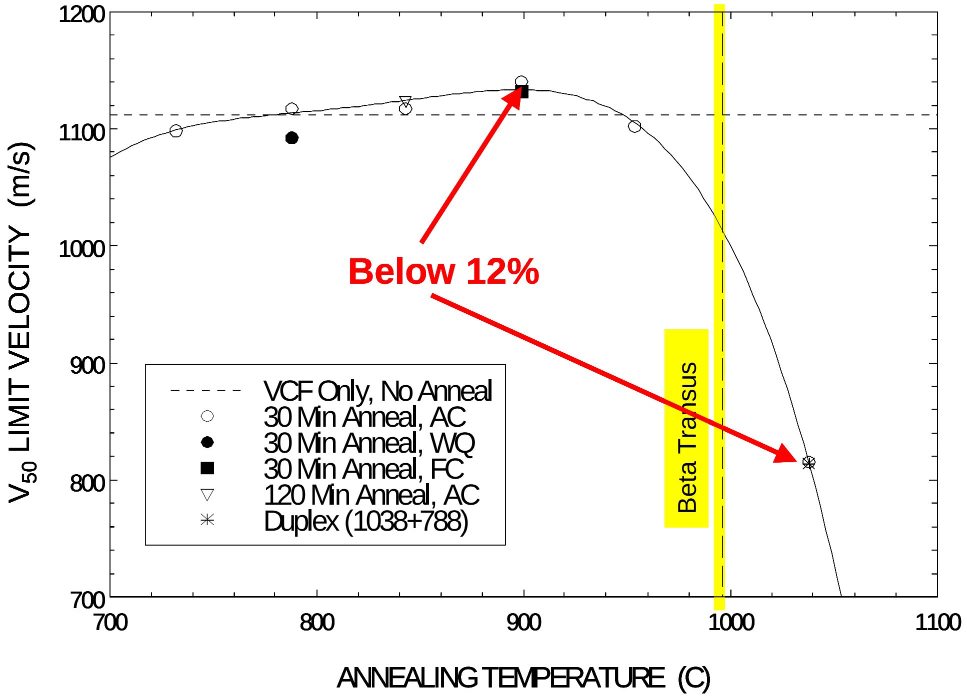


Figure 9. Effect of Transverse Elongation with Annealing Temperature

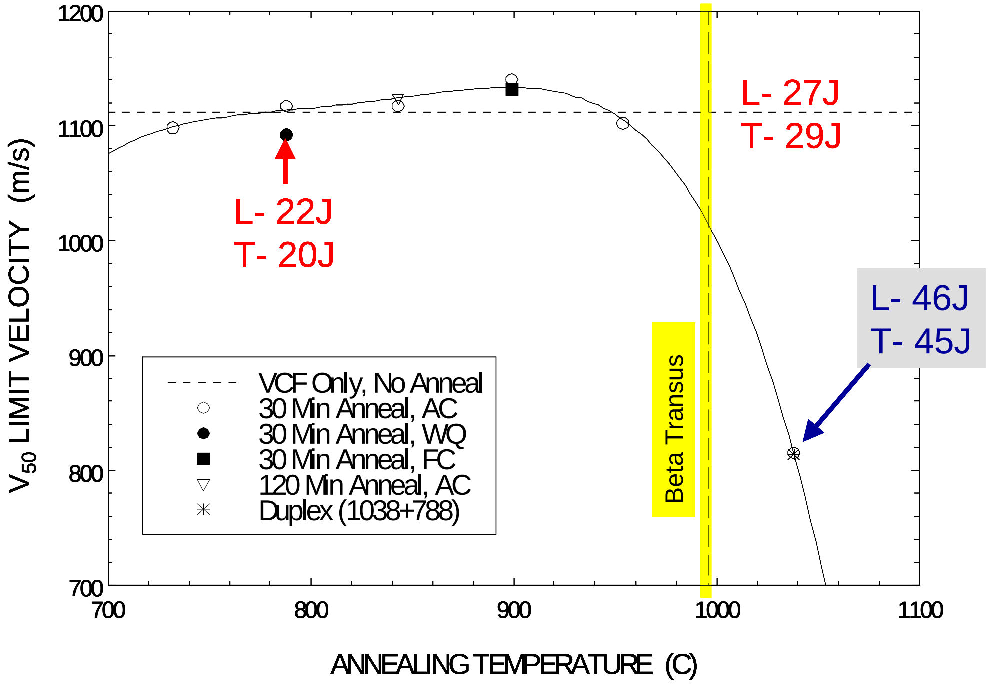


Figure 10. Effect on Charpy Impact Results with Annealing Temperature

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^{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

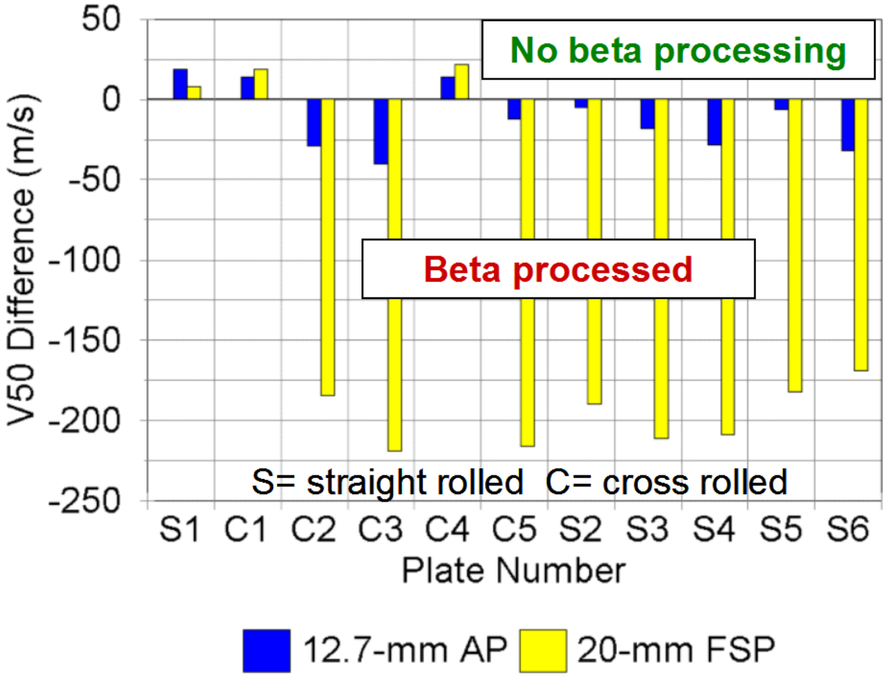


Figure 11. Beta processed Ti-6Al-4V Plate Compared to Alpha-Beta Processed Plate

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 the 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

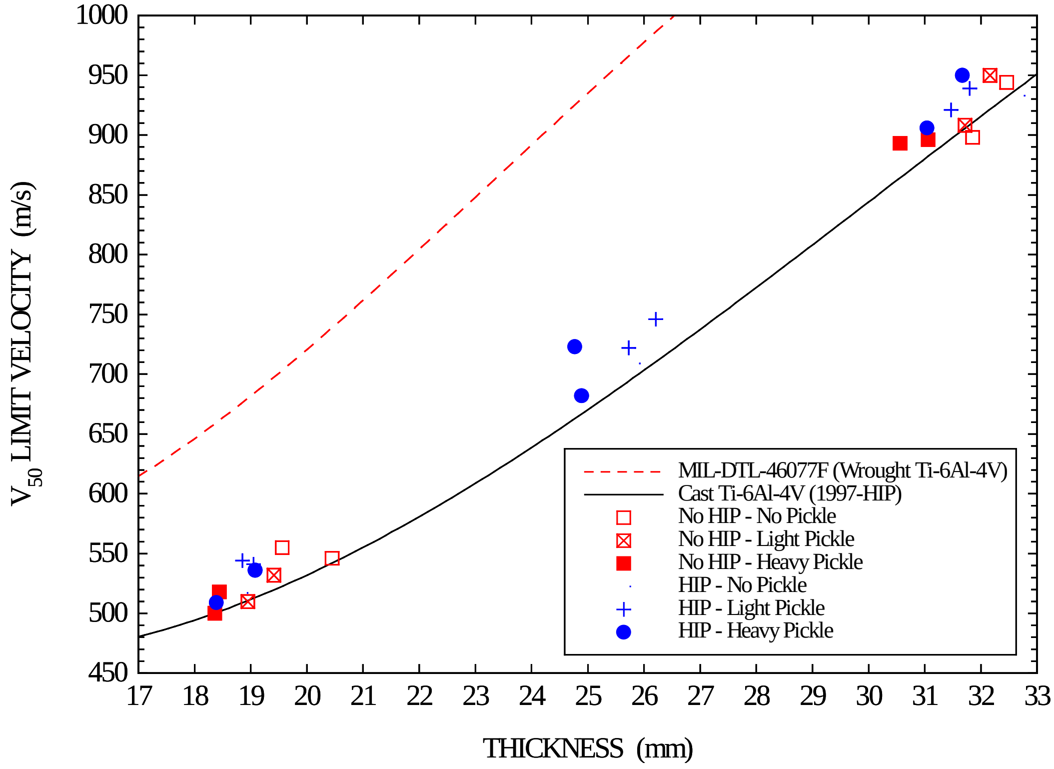


Figure 12. Ballistic Performance of 20mm FSP vs Wrought and Cast Titanium

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.

SHAPED CHARGE PROTECTION OF TITANIUM

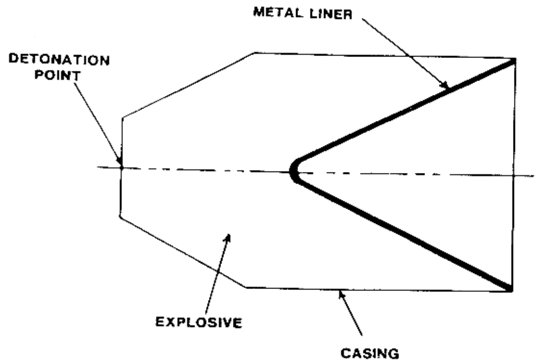


Figure 14. Shaped Charge Warhead

The primary discussion to date has related to the penetration of titanium by kinetic energy projectiles or fragments, but titanium also has excellent performance against shaped charge (SC) warheads [17]. Figure 1 showed the performance of a L/D 13 long rod tungsten penetrator as a function of velocity, with the highest impact velocity about 2.6 km/s. A typical SC is shown in Figure 14 and Figure 15 shows the sequence of flash x-rays illustrating the functioning of the warhead [18-19]. The conical copper liner is embedded in a cylinder of explosive which is detonated at the base of the explosive and the resultant detonation wave collapses the liner on the axis of the charge. This collapse causes a high velocity jet to be ejected forward. Depending on the design, the tip of the jet is traveling about 10 km/s with the tail traveling about 3 km/s. This velocity gradient causes the jet to stretch and elongate, creating very high L/D ratios. Shaped charge penetration is basically hydrodynamic where jet penetration is more a function of the relative densities of the penetrator and target and jet length; strength effects approach 0. Figure 16 compares the semi-infinite penetration of a 102mm tantalum shaped charge warhead into a stack of RHA steel and Ti-6Al-4V titanium [20-22]. The titanium had a mass efficiency 1.6 times that of the RHA, but had a space efficiency of 0.9, i.e., requires about 10% more thickness to equal the penetration into RHA. To put this in terms of pounds/ft^2, 1028 lbs of steel is needed to stop the penetration of the warhead versus 635 lbs of titanium (697mm of titanium). Overall, titanium offers excellent kinetic energy and shaped charge penetration resistance.

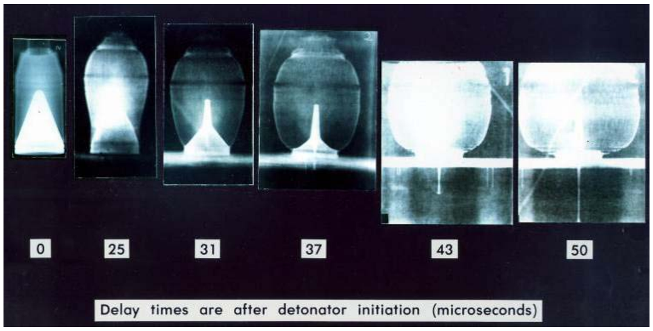


Figure 15. Formation of SC Jet

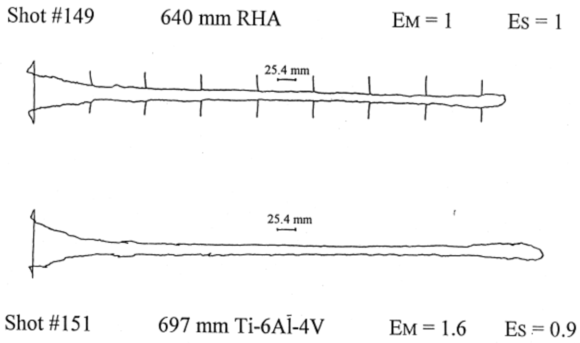


Figure 16. SC Penetration of Titanium

TITANIUM FORGINGS

Figure 17 shows an application of the forging of titanium for military application for ground vehicles [23]. The forging has increased strength similar to wrought rolled plate due to the mechanical working of the metal. 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 to the previous steel hatch.

Figure 17. M2A2 Titanium Commanders Hatch

TITANIUM HOT PRESSED NET SHAPE BODY ARMOR PLATES

In 2005-2006, ARL examined the use of hot pressing net shape compound angle titanium body armor inserts in conjunction with BAE Advanced Materials of Vista, CA. The equipment used was the same hot presses used to fabricate boron carbide ceramic plates for use in body armors. Figure 18 shows a completed BAE hot pressed titanium ballistic insert [24]. Plates were fabricated from both Class 3 and 4 titanium alloys under MIL-DTL-46077G. Perciballi of ArmorWorks, Tempe, AZ also examined titanium body armor plates in 1998 [25].

TITANIUM COMPOSITES/LAMINATES

Figure 18. Hot-Pressed Net Shape Titanium Body Armor Plate

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 19 where a titanium plate is mechanically attached to an aluminum back plate [18-19]. ARL examined a prototype titanium appliqué on a M113A3 personnel carrier aluminum structure and had excellent ballistic performance over heavier steel based appliqués. For newer structures, 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 remaining fragments or projectile.

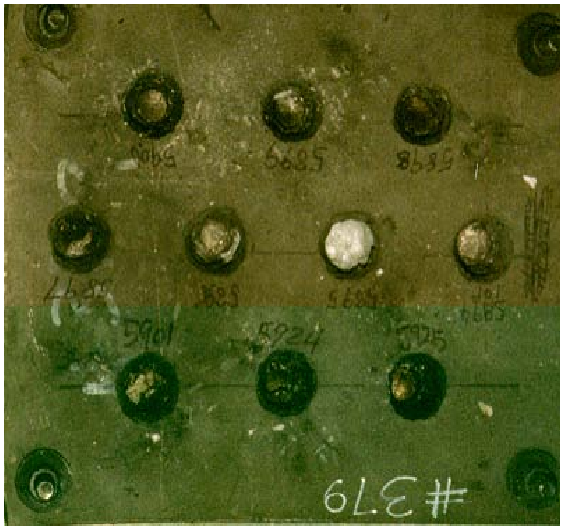


Figure 19. Multiple Impacts on a Titanium/ Aluminum Laminate

DUAL HARD TITANIUM

Figure 20 conceptually shows a titanium dual hard metallurgically bonded laminate similar in concept to dual hard steel. A softer rear plate can reduce spalling of the rear surface and contribute to higher performance.

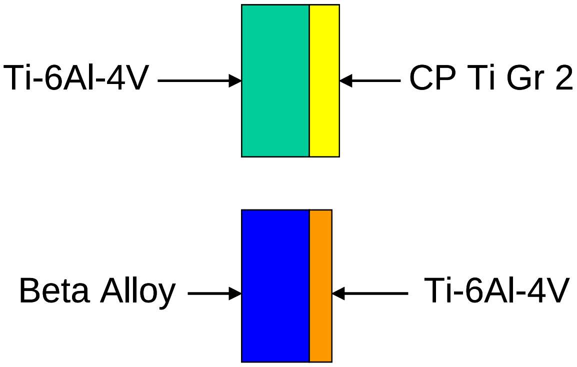


Figure 20. Dual Hard Titanium Concept

These 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 earliest work in this area was undertaken between 1969 and 1976 at both Lockheed Missile and New York State University for the former US Army Materials and Mechanics Research Center, now the Materials and Research Directorate of ARL [26-29]. At that time, a Ti-3Si-Fe-0.5N front face alloy was roll bonded to a Ti-7Al-2.5Mo back plate and then heat-treated. The observation that a front hardness of 60 Rc or greater was optimum for ballistic resistance and maximum spall resistance occurred when the thickness ratio of 70/30 was noted. Today, these plates could be metallurgically bonded by rolling, diffusion bonding, hot-isostatically pressing or explosive welding. ARL has investigated all four types of bonding and found the ballistic performance can improve by10-25% depending on the threat and cross-sectional areal density [30-31]. Figure 21 shows the cross-section of a hot isostatically pressed Ti-6Al-4V/CP titanium laminate after an overmatch perforation of a fragment simulator. The penetrator impacted from the bottom and a ductile petalling failure of the CP titanium is evident without spalling. This combination was about 10% better that a single Ti-6AL-4V weight equivalent plate. This research area probably offers the best direction for ballistic application of titanium to future combat systems and these excellent older references should be revisited.

Figure 21. Hot Isostatically Pressed Ti-6Al-4V/CP Titanium Dual Hard Laminate

FUNCTIONALLY GRADED TIB/TITANIUM

The development of functionally graded materials (FGM) using ceramics and metals may offer even higher performance than dual hardness metal laminates, but the material complexity is more demanding. BAE Advanced Materials, under contract to ARL, 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 [32]. As seen in Figure 22, 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

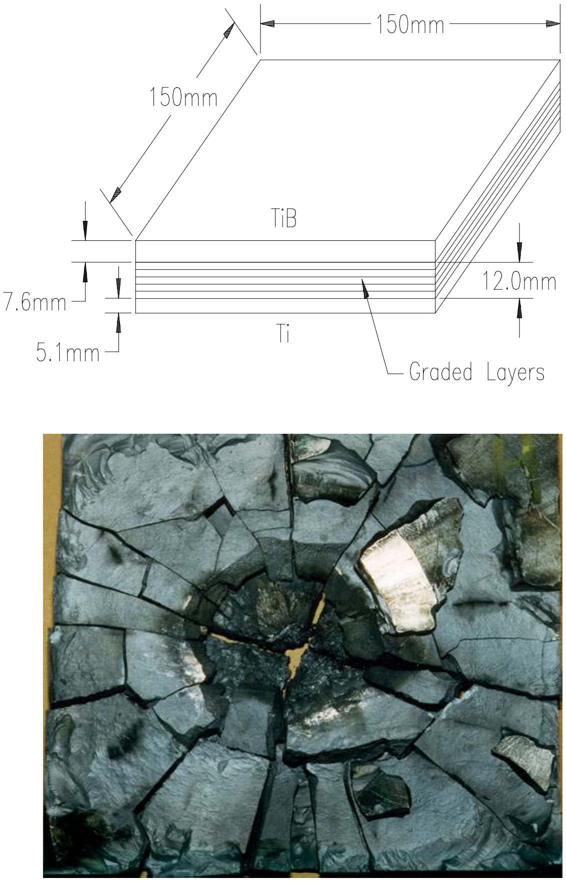


Figure 22 Functionally Graded Titanium Monoboride/Titanium Plate

gradient materials produced in the world by a practical process and represent an advancement in this technology area.

HOT ISOSTATICALLY PRESSED CERAMIC/TITANIUM MATRICES

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 [33]. This process has led to the left image of Figure 23 that 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 front metal ceramic interface with little damage to the ceramic. Again, then thermal expansion coefficients and elastic moduli of the layers as well as critical back plate stiffness drive this mechanism. One fabrication method for incapsulation in a metallic structure is to hot isostatically press the titanium around the ceramic as seen in the two images of Figure 24 [34].

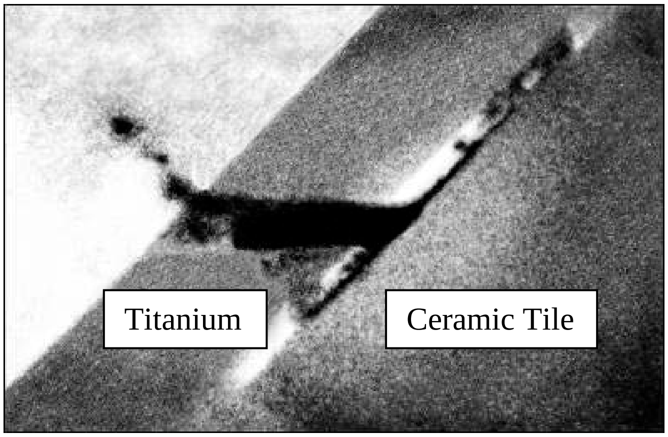


Figure 23. Interface Dwell at the Titanium/Ceramic Interface

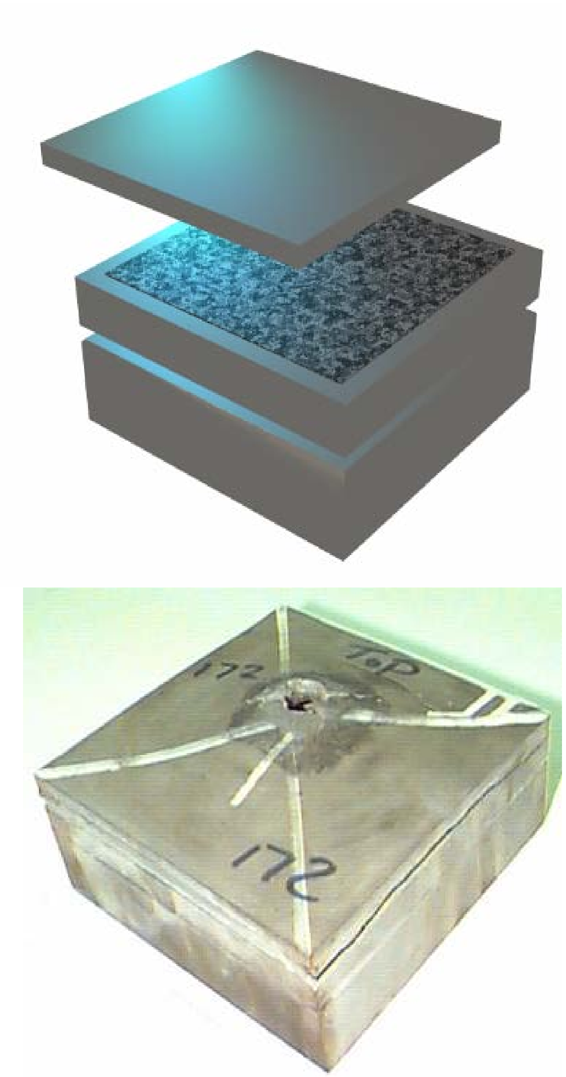
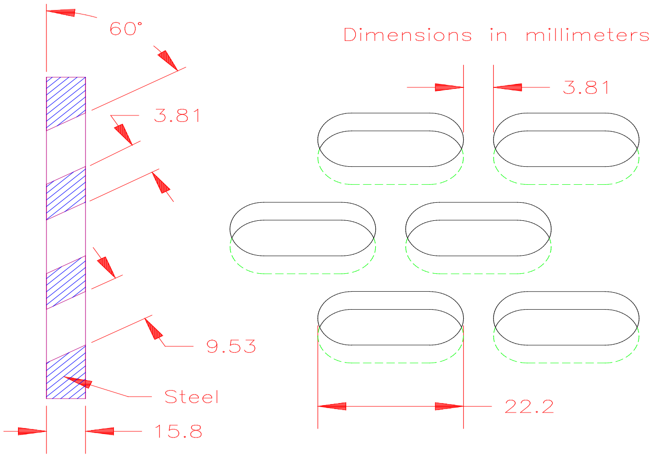


Figure 24. Hot Isostatically Pressed Ceramic in Titanium Matrices

CAST P900 TITANIUM TIPPING PLATES

The development of single plate cast P900 steel tipping plates by ARL in the late 1980's provided a significant improvement over single homogeneous steel armor plates when used as the strike face for a spaced armor or appliqué armor system. The 1991 patent provides the details of the cross-sectional design of angular holes that is still used today [35]. As seen in Figure 25, the holes are repetitively placed at a 60^o angle such that the areal weight is about 50% of a solid plate. The non-homogeneous cross-section causes the projectile to tip and breakup; the disrupted fragments can then be captured in the base vehicle structure [18-19]. In 2007, ARL published military specification MIL-PRF-32269 (MR) on Perforated Homogeneous Steel Armor that set the requirements for production and acceptance of this technology [36]. Concurrently, ARL funded the development of titanium P900 using two different casting techniques to demonstrate the feasibility of producing lower weight net shape titanium castings that



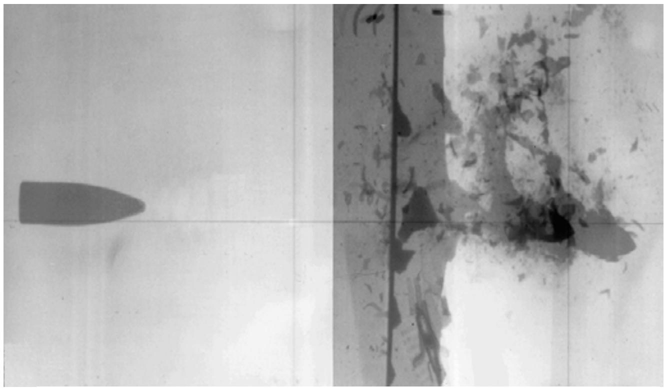


Figure 25. X-ray of a 14.5-mm Projectile Impacting a Single P900 Plate

provided the required disruption or tipping action on the impacting penetrator. The intent was to demonstrate a P900 titanium plate that met the general performance requirements of the steel military specification, but provided increased weight reduction for military platforms.

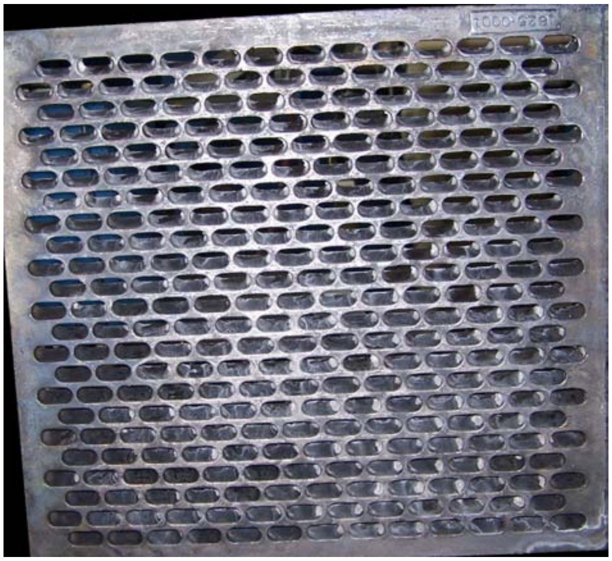


Figure 26. Pacific Cast Technologies Cast P900 Titanium Plate

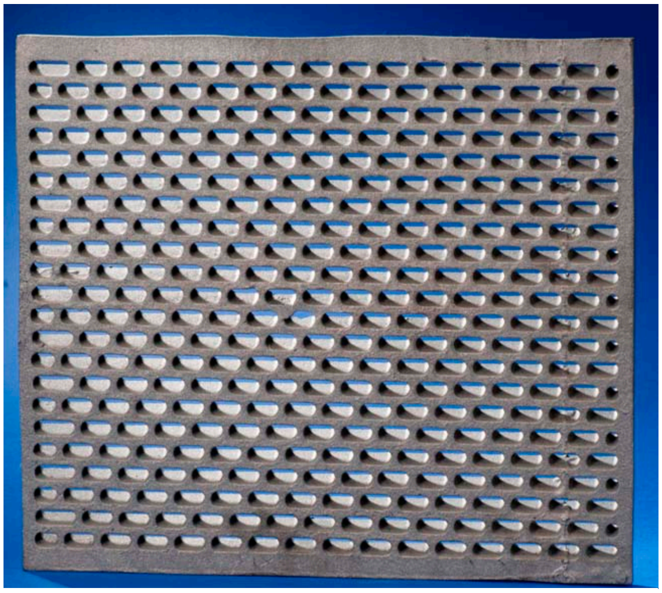


Figure 27. ATI Wah Chang Cast P900 Titanium Plate

Two casting technologies were selected for prototyping the P900 plates. Figure 26 shows a 15” X 15” X 0.625” cast titanium P900 plate produced by Pacific Cast Technologies of Albany, OR that was produced using StereoLithography rapid prototyping technology and precision investment castings [37]. Figure 27 shows a 17” X 17” X 0.625” cast titanium P900 plate produced by ATI Wah Chang of Albany, OR using rammed graphite mold processing and lost foam casting technology [38]. Both companies were successful in producing plates that met the requirements of military specification and this technology needs to be further developed using different alloys and heat treatments. Besides ground vehicle application, the ability to cast to net shape has advantages for application to aerospace protection requirements where weight is a critical factor. This was further conceptualized by ARL for application in “Perforated Fuselage Armor” that would incorporate both ballistic protection mechanisms and structural components [39].

MIL-DTL-46077G CLASS 4 TITANIUM ALLOYS

As mentioned earlier, MIL-DTL-46077G was created to provide an incentive to the titanium industry to develop non-aerospace grades of ballistic titanium [4]. 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 oxygen and Class 4 goes a step further by removing the requirements for aluminum and vanadium. The intent is to develop non-aerospace alloys for protection requirements that can take full advantages of low-cost processing and reduced production processes that provide the required ballistic plate. 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 military specification.

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 production 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 and lower cost electron beam or plasma beam processing. ARL considers this technical direction as the best opportunity for increasing titanium applications for ground applications in the future, whether as a standalone material or use in combination with other materials. Figure 28 shows the rear view of a production acceptance test of a 4.0” Ti-6Al-4V Class 3 plate that easily passed the MIL-DTL-46077G specification [40]. The test projectile here is a 30mm tungsten projectile and the development of the spall disk can be seen as the velocities are increased. Shot 13569 has an impact velocity just below the resultant V_{50} and the spall disk is almost fully separated.

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. Figure 29 shows the large bend capabilities available in MIL-DTL-46077G Class 4 ATI 425-MIL™ titanium plate [41].

Figure 28. Production Acceptance Testing on a 4.00” Class 3 MIL-DTL-46077G Plate

Figure 29. Bend Capabilities of ATI 425-MIL™ Class 4 MIL-DTL-46077G Plate

Class 4 alloys may increase perceived production issues, such as qualification costs associated with legacy vehicle production, but this direction offers the best potential to increase applications for 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. While some effort to utilize titanium plate as appliqués on trucks in the Korean War, the earliest use of titanium for a structural application in a combat vehicle is shown in Figure 29 of a 1960 Detroit Arsenal prototype of a titanium cab on an ONTOS tracked vehicle [42]. 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 structure and armor components for the world's combat vehicles remain steel or aluminum based and large amounts of aluminum appliqués 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.

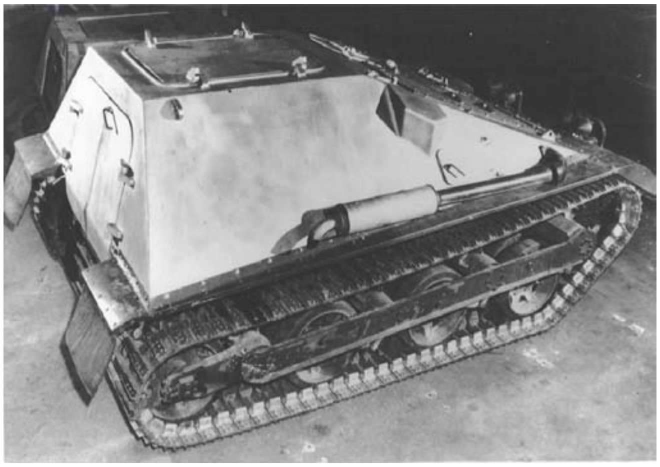


Figure 29. 1960 Detroit Arsenal Titanium Cab on an ONTOS Tracked Vehicle

One of the best illustrations of titanium on a current legacy system is shown in Figure 30 on the M1A2 Abrams tank where a concerted effort was made to reduce weight of components on the chassis [43-44]. 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 31 shows the M2A2 Bradley Fighting Vehicle and two uses of titanium have been incorporated into design [43]. The commanders 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 32,was selected in 1997 by a joint US Army/Marine Corps initiative to replace the existing inventory of M198 155mm towed howitzers [45]. 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.

Current application of titanium is also found on two versions of the Stryker family of Vehicles [46]. Figure 33 shows the Stryker Mobile Protected Gun System and the Gun Pod is fabricated from titanium. Also shown in Figure 34 is the titanium Gunners Protection Kit on the RV and FSV versions of the Stryker. Titanium was used to reduce weight for the application

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 35 shows the Pegasus electric drive wheeled prototype developed by BAE Systems that utilized both a lower and upper titanium welded structure [47]. 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.

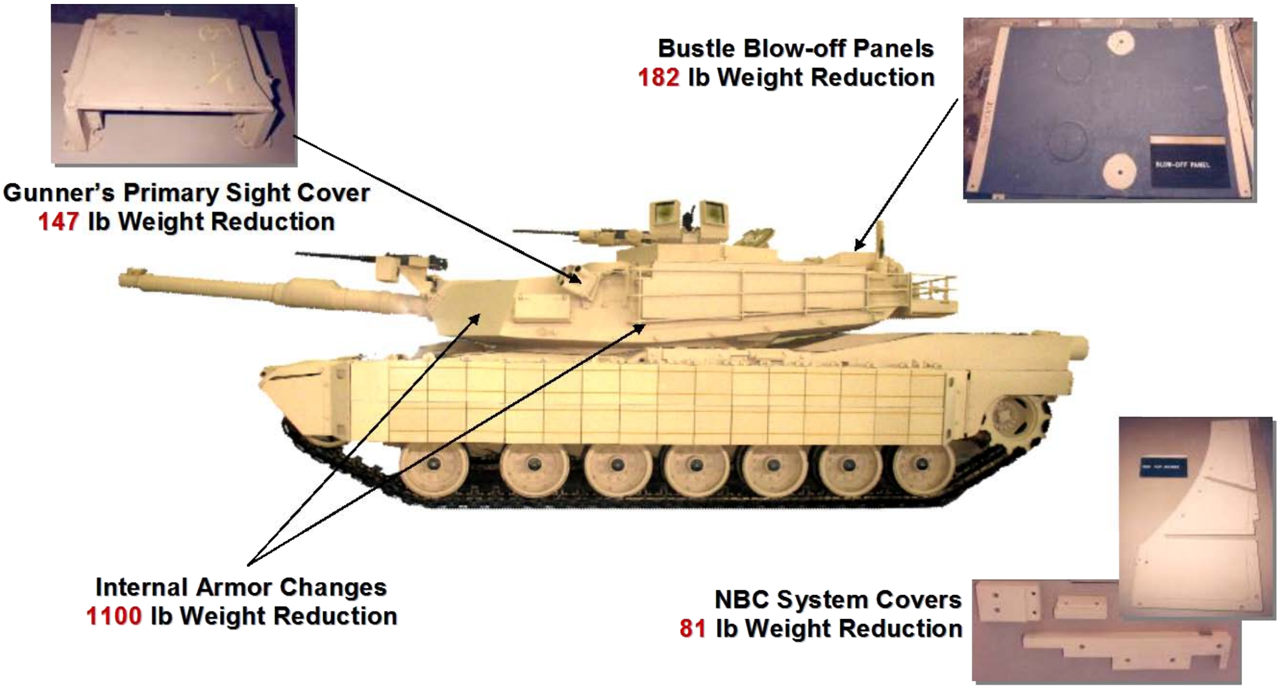


Figure 30. Titanium Weight Reduction Program for M1A2 Abrams Battle Tank

Figure 31. Titanium Commanders Hatch and Roof Applique on M2A2 Bradley Fighting Vehicle

Figure 32. M777A1 Ultra-light Field Howitzer

Figure 33. Titanium Gunners Overhead Protected Gun System on RV and RSV Stryker

Figure 34. Stryker Mobile Protected Gun System Titanium Gun Pod

Figure 35. BAE Pegasus Titanium Wheeled Prototype

The latest prototype titanium vehicle structure was an early Future Combat Vehicle hull section that was used to test composite armors (Figure 36) [48]. 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.

Figure 36. Prototype Future Combat Vehicle Titanium Hull Section

CONCLUSIONS

This paper has provided an overview on the use of titanium alloys in military ground systems. The emphasis has been to examine the design and processing aspects in the application of this lightweight, high strength metal and emphasize cost/performance tradeoffs. With major emphasis on lightening future ground platforms, low cost grades of titanium, particularly Class 4 alloys outside the standard Ti-6Al-4V alloy family, can provide both structural and ballistic solutions. Further research into dual hard titanium offers further weight reduction and ballistic performance. Both these areas can translate into reduced material costs that make titanium more competitive as compared to other armor technologies.

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. Gooch, W. and Burkins, M., *A Ballistic Evaluation of Ti-6AL-4V vs. Long Rod Penetrators*, NATO Applied Vehicle Technology Panel, Loen, Norway, 7-11 May 2001.
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., Walters W., Kozhushko A. and Sinani A., *Target Strength Effect on Penetration l by Shaped Charge Jets*, Hypervelocity Impact Society Symposium, Galveston, Texas, 6-10 November 2000
18. Gooch, W., *An Overview of Protection Technology for Ground and Space Applications*, Second Australian Congress on Applied Mechanics, Canberra, Australia, 10-12 February 1999
19. Gooch, W., *An Overview of Protection Technology for Ground and Space Applications,* NATO Applied Vehicle Technology Panel, Aalborg, Denmark, 23-26 September 2002
20. 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

21. Walters W., Gooch W. and Burkins M., *The Penetration Resistance of a Titanium Alloy against Jets from Tantalum Shaped Charge Liners,* Journal of Combustion, Explosion and Shock Waves, Vol 36, No. 6, 2000, pages 745-750

22. Walters W., Gooch W. and Burkins M., *The Penetration Resistance of a Titanium Alloy against Jets from Tantalum Shaped Charge Liners,* International Journal of Impact Engineering 26, 2001, Pages 823-830

23. Burkins, M., *The Design and Application of Titanium Alloys for U.S. Army Platforms*, Military Panel, International Titanium Association Titanium 2008, September 24, 2008.

24. Photo provided courtesy Rich Palicka, BAE Advanced Materials Division, Vista, CA

25. Perciballi, W., *Titanium Body Armor Plates*, SBIR Phase 1 Final Report, Contract USZA22-98-P-0007, 1998

26. Farrar P., *Development of Improved Titanium Armor,* AMMRC CR-69-16 (AD0697178), New York University, August 1969

27. Perkins R. and Rennhack E., *Evaluation of Dual-Hardness Titanium Alloy Armor,* AMMRC CR 70-3, (AD0702238), Lockheed Missiles and Space Company, January 1970

28. Perkins R. and Rennhack E., *Processing and Ballistic Evaluation of Dual-Hardness Titanium Armor,* AMMRC CTR 74-17 (AD0777809), Lockheed Missiles and Space Company, April 1974

29. Perkins R. and Rennhack E., *Dual Hardness Titanium Alloy Composite Armor,* AMMRC CR 76-01, Lockheed Missiles and Space Company, January 1976

30. Hernandez V., Unpublished Research on *Ballistic Evaluation of Bonding Methods for Titanium,* December 2006.

31. Bruchey W. and Burkins M., *Suppression of Material Failure Modes in Titanium Armors*, ARL-TR-3124, December 2003

32. 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

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

34. 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.

35. Gooch, W., Burkins, M., Mills, L., Ogilvy, J. and Ricchiazzi, A., *Cast Single Plate P900 Armor*, U.S. Patent 5007326, April 16, 1991

36. MIL-PRF-32269 (MR), *Performance Specification - Perforated Homogeneous Steel Armor,* 18 October 2007

37. Photo provided courtesy of Pacific Cast Technologies, Albany, OR

38. Photo provided courtesy of ATI Wah Chang, Albany, OR

39. Gooch, W. and Burkins, M., *Perforated Fuselage Armor Concept*, National Specialist Meeting on Rotocraft Structures and Survivability, American Helicopter Society, Williamsburg, VA, 25-27 October 2005

40. ARL ballistic certification on 4.00” Titanium Plate in accordance with MIL-DTL-46077G

41. Photo provided by Larry Martin, ATI Defense, Washington, PA

42. Gooch, W., *The Design and Application of Titanium Alloys for U.S. Army Platforms*, Military Panel, International Titanium Association Titanium 2008, September 24, 2008

43. Figure provided courtesy of PEO CS&CSS, PM Abrams, Warren, MI

44. 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,

45. Website, Army-Technology.com

46. Photos provided courtesy of Terry Dean, PM Stryker, PEO CS&CSS, Warren, MI

47. Figure provided courtesy of BAE Systems, Santa Clara, CA

48. Figure provided courtesy of BAE Systems, Santa Clara, CA

RDECOM

THE DESIGN AND APPLICATION OF TITANIUM ALLOYS FOR US ARMY PLATFORMS

TITANIUM 2010
MILITARY PANEL
Orlando, Florida
3-6 October 2010

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

William. A. Gooch
U.S. Army Research Laboratory
Weapons and Materials Research Directorate
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Introduction

- Titanium was first examined for armor applications in 1950 by the Watertown Arsenal and Ti-6Al-4V become the main alloy of interest

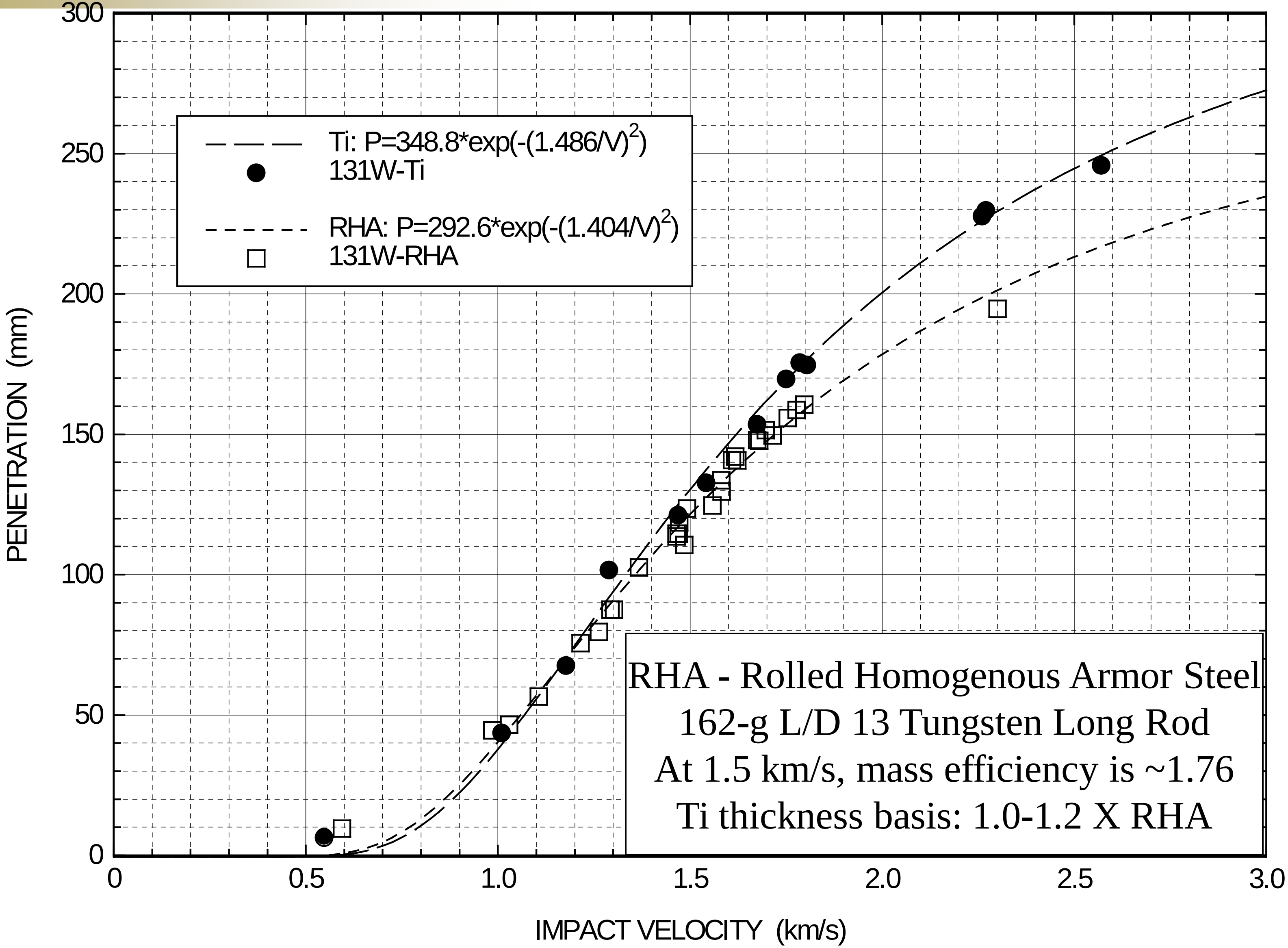
- The main advantage of titanium relates to the lower density at equal or higher strengths than rolled homogenous armor steel of equal thickness (23.2 vs 40.8 psf for 1" board foot ~43% weight reduction)

- This is the fourth year ARL has provided this Overview at the ITA and the written paper provides a detailed review of the ballistic aspects of titanium alloys

- In this short time, I would like to emphasize two technical areas that can lead to increased use of titanium alloys in the future:
  - Class 3 and Class 4 Titanium alloys under MIL-DTL-46077G
  - Dual hard titanium

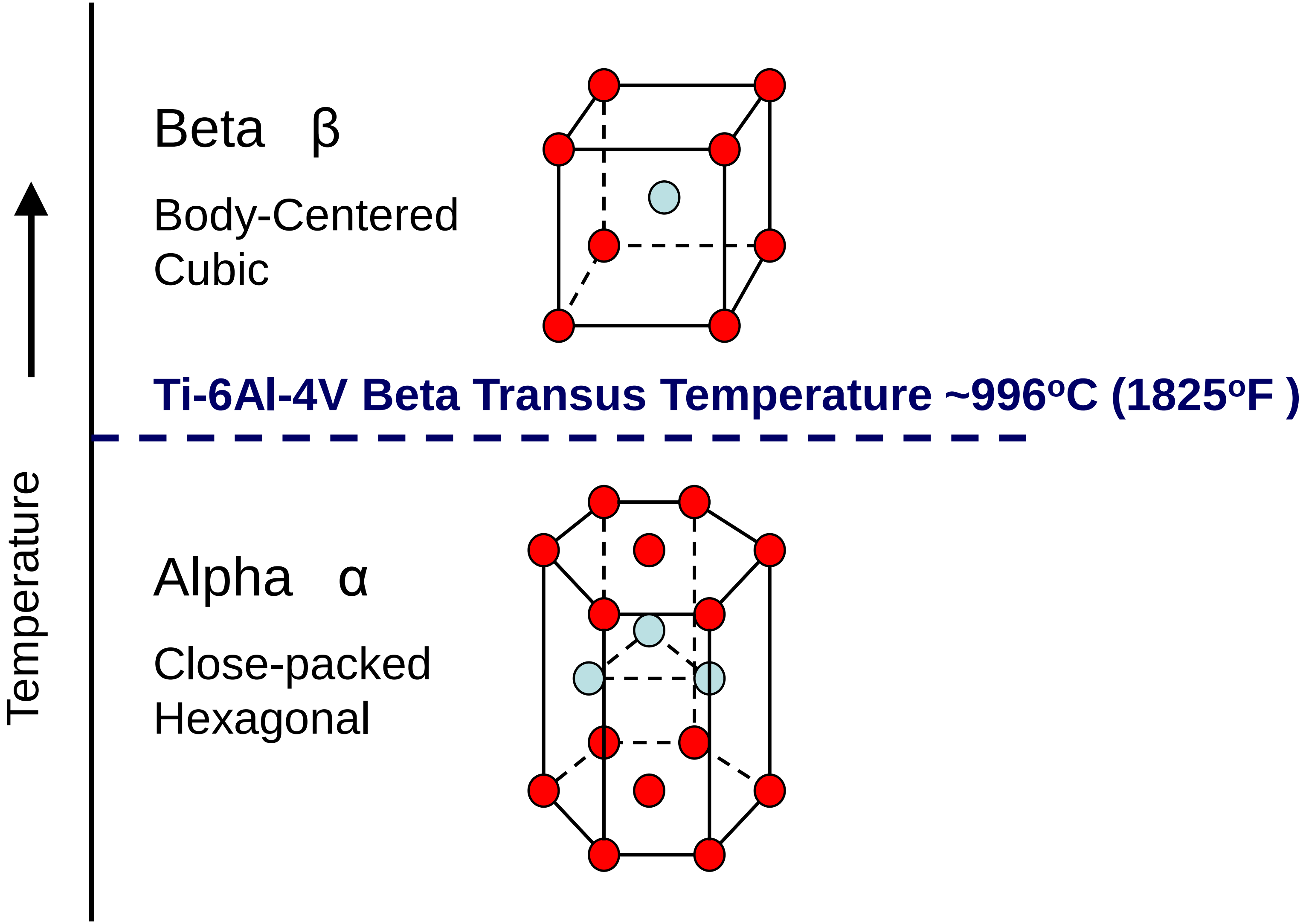
- The presentation will show some new applications and end with an overview of current and proposed future applications of titanium for military ground vehicles

KE 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

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



Temperature

Beta β

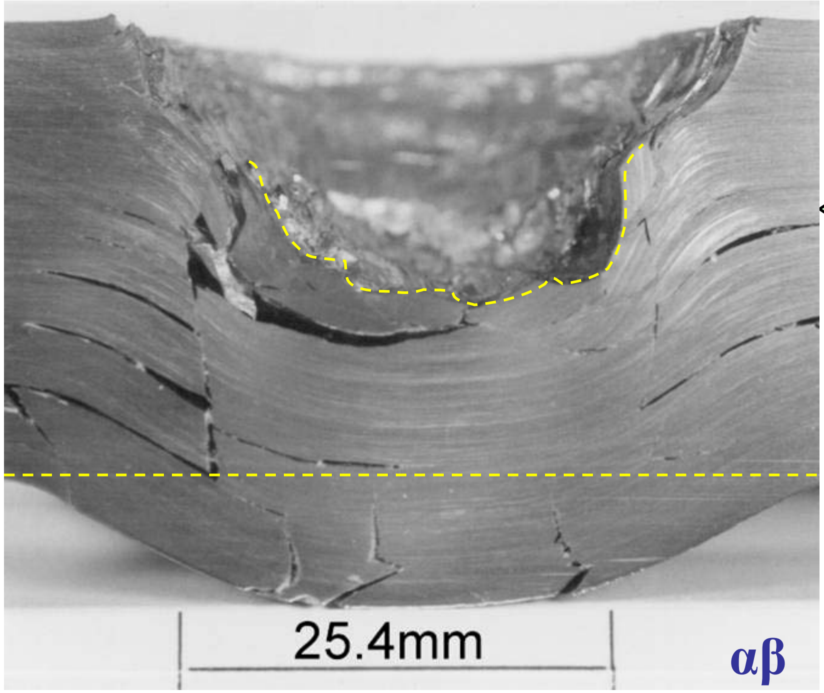
Body-Centered Cubic

Ti-6Al-4V Beta Transus Temperature ~996^{o}C (1825^{o}F)

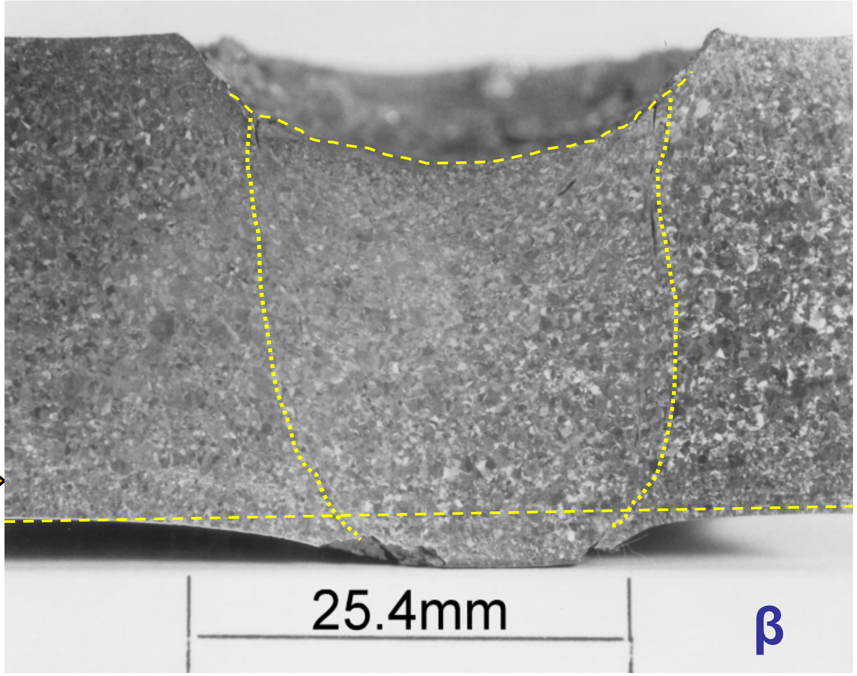
Alpha α

Close-packed Hexagonal

Failure Analysis of 20mm Fragment Simulating Projectile Impact



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

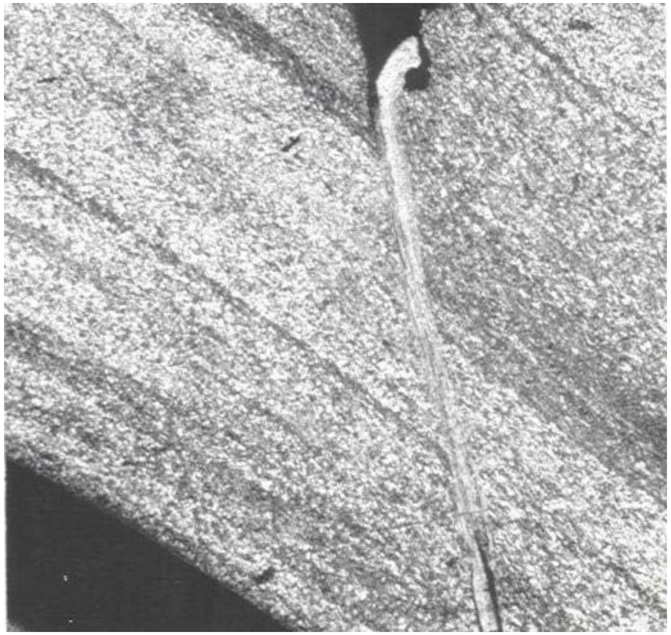


Failure by low-energy plugging

Adiabatic Shear Bands in Titanium

Strain causes localized heating

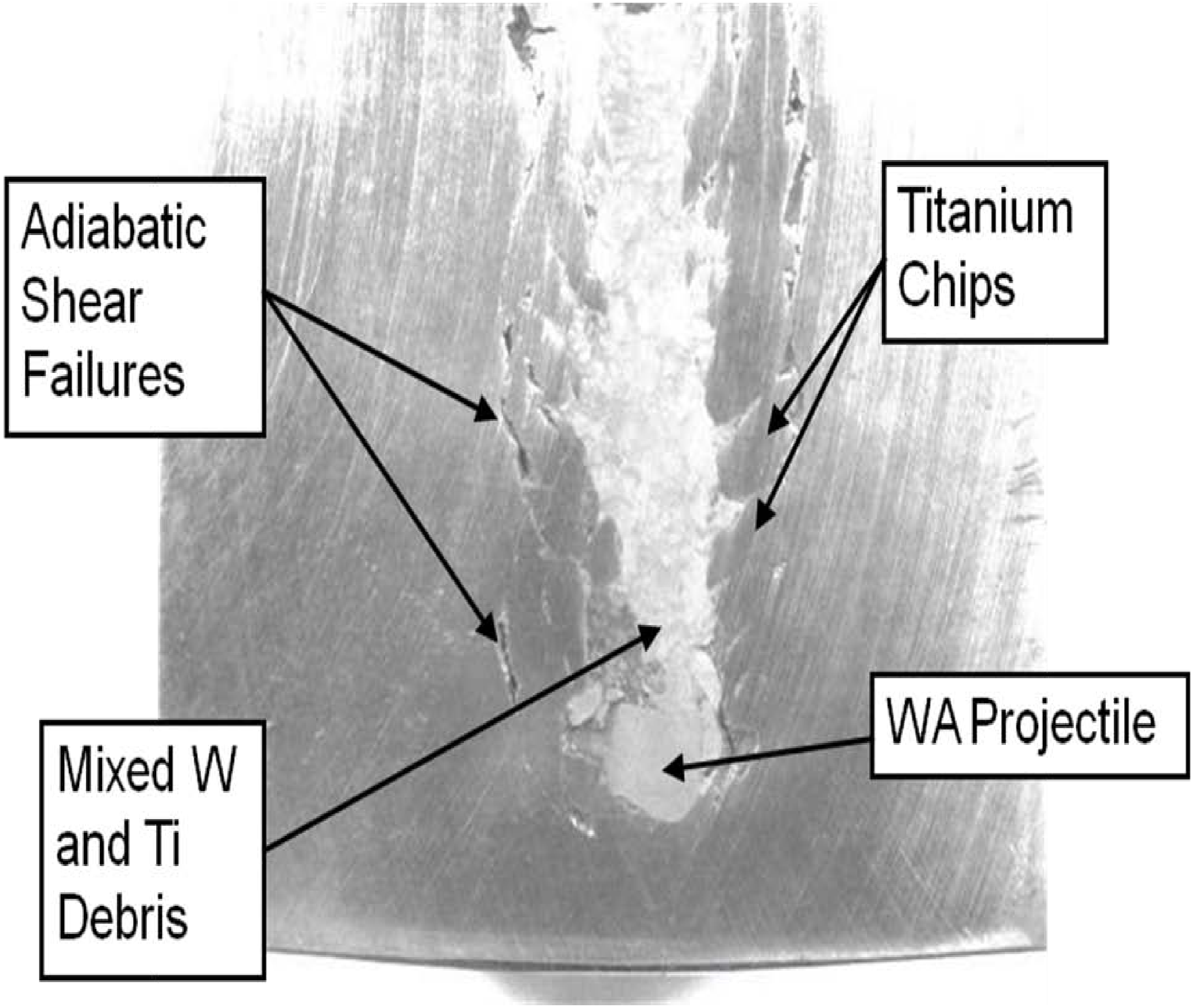
Heat cannot dissipate



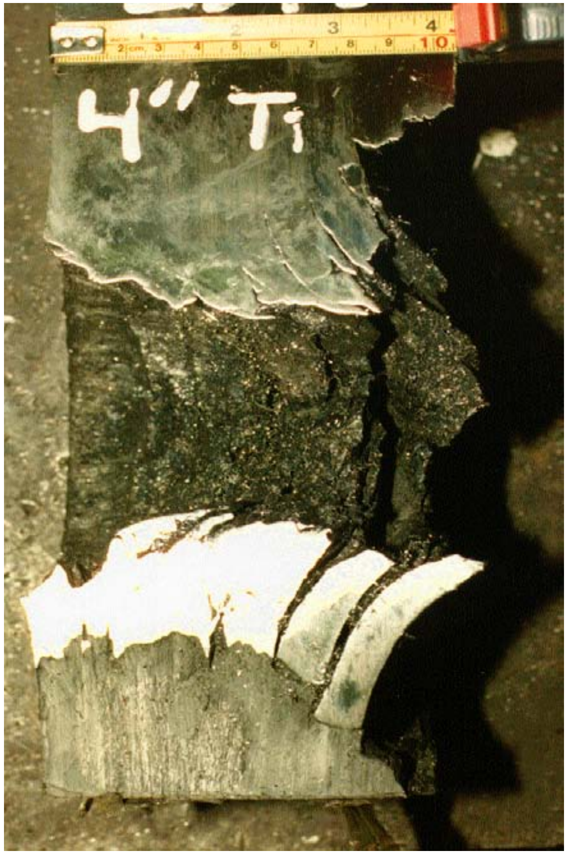
Material softens

Additional strain in soft areas

Deep Penetration into Titanium Showing Adiabatic Shear Bands



Spall Plug Breakout of Titanium



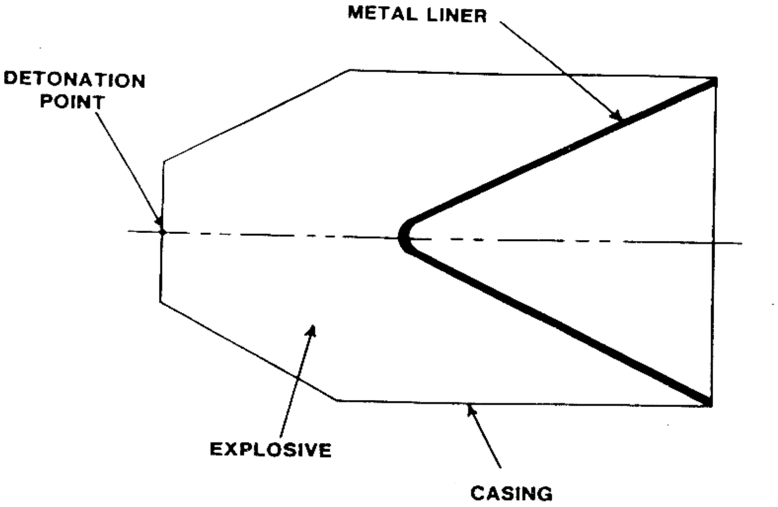
SPALL RING
BREAKOUT

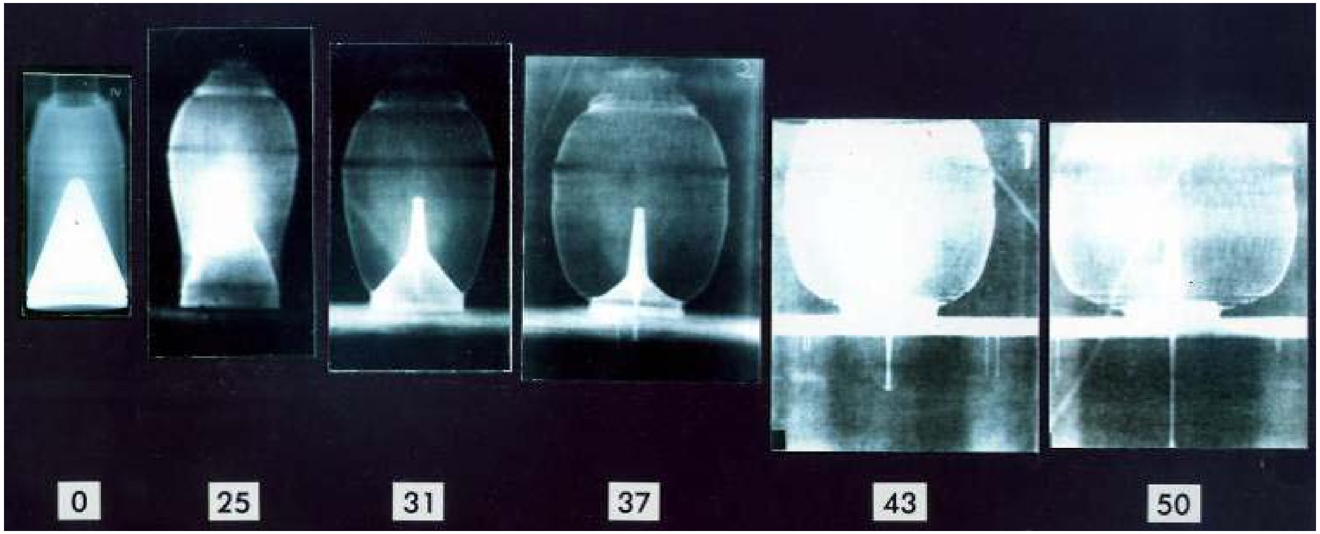
SHEAR BANDS AND
DELAMINATION

PENETRATOR
CHANNEL

SHEAR BANDS AND
DELAMINATION

Shaped Charge Penetration

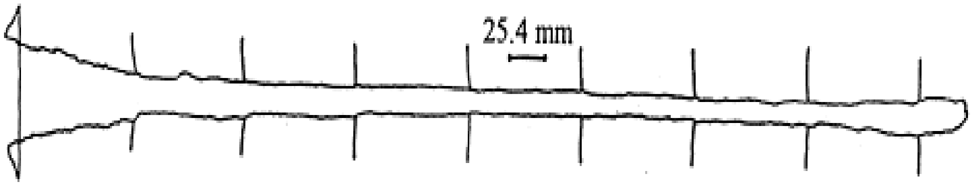




Formation of SC Jet

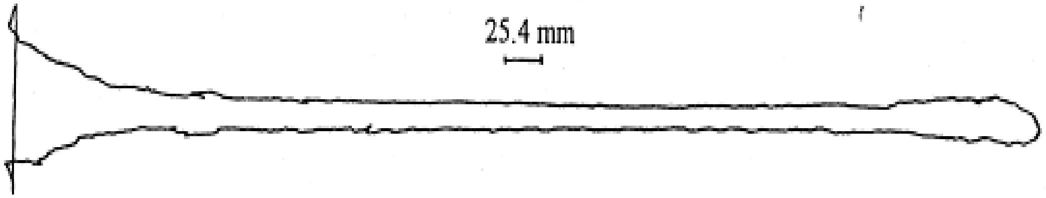
Shaped Charge Penetration into Titanium

Shot #149 640 mm RHA $E_M = 1$ $E_S = 1$



~25 inches
1028 lbs/ft^2

102mm tantalum liner



~27 inches
635 lbs/ft^2

Shot #151 697 mm Ti-6Al-4V $E_M = 1.6$ $E_S = 0.9$

Titanium MIL-DTL-46077F & G

	Chemistry	Max. O_2 Content	Comments
Class 1	6AL- 4V	0.14%	***ELI*** - 10% Elongation Minimum
Class 2	6AL- 4V	0.20%	***Historical Armor Alloy*** 6% Elongation Minimum
Class 3	6AL- 4V	0.30%	***Higher Scrap/O_2 Content*** Electron Beam/Plasma Melting
Class 4	Not Limited	0.30%	***Lower cost alloying*** Non Aerospace Alloys

All four classes have the same minimum strength and ballistic requirements.

Expanded thickness range: 3mm-101.6mm

Emphasis 1

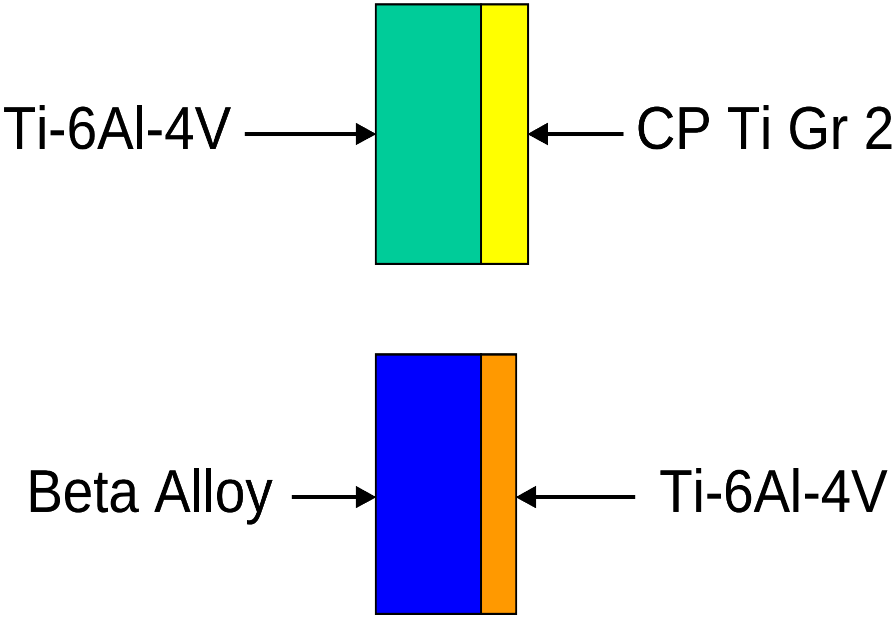
Class 3 and 4 MIL-DTL-46077G Plate

Production Acceptance Testing of a TIMET 4.00” Class 3 Plate

Bend Capabilities of ATI 425-MIL™ Class 4 Armor Plate

Titanium Laminates/Dual Hard Titanium

Titanium Wrought Plate Bolted to an Aluminum Rear Plate

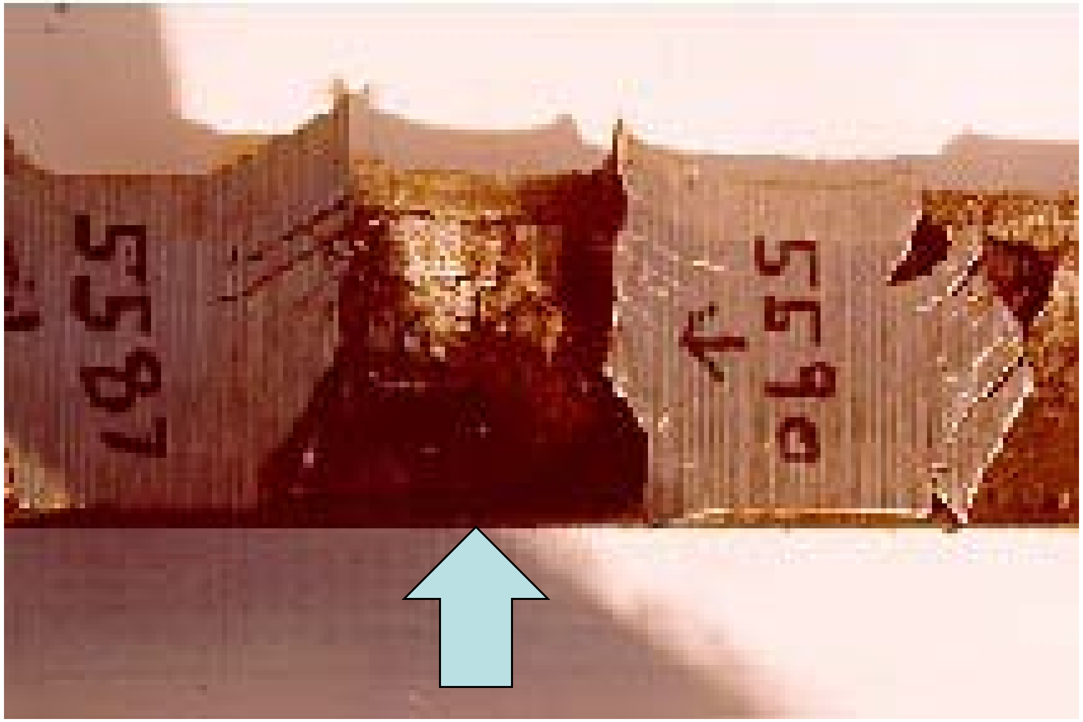


Ti-6Al-4V → ← CP Ti Gr 2

Beta Alloy → ← Ti-6Al-4V

Dual Hard Titanium Concepts

Emphasis 2
Titanium Dual Hard Armor



CP

Ti-6Al-4V

ARL Hot Isostatically Pressed Ti-6Al-4V/CP Titanium Dual Hard Laminate

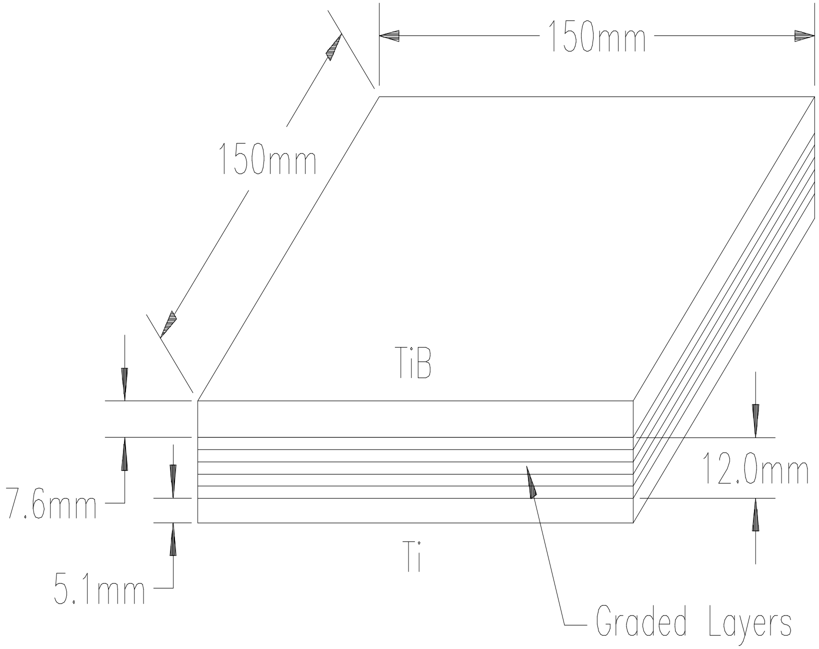
References 26-29 in paper - Dual Hard Titanium reports from 1969-1976

New Potential Applications
Titanium Body Armor Plate

BAE Advanced Materials Hot-Pressed Net Shape Titanium

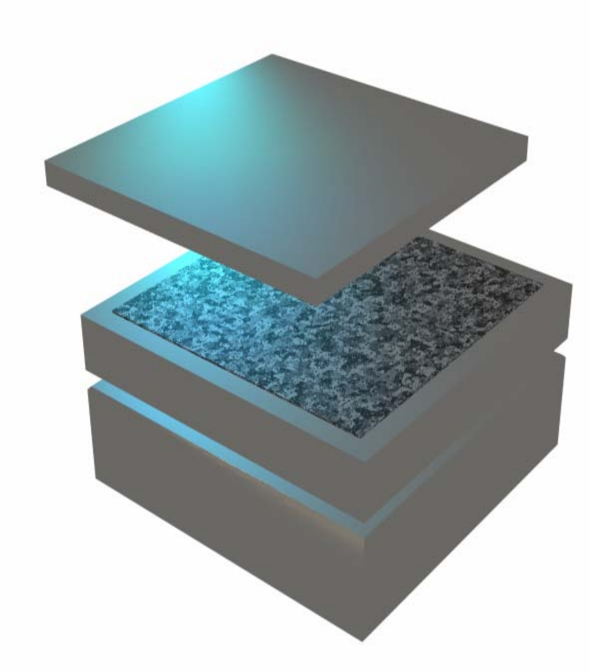
Double Compound Angle Body Armor Plate

Functionally Graded Titanium Monoboride/Titanium Plate

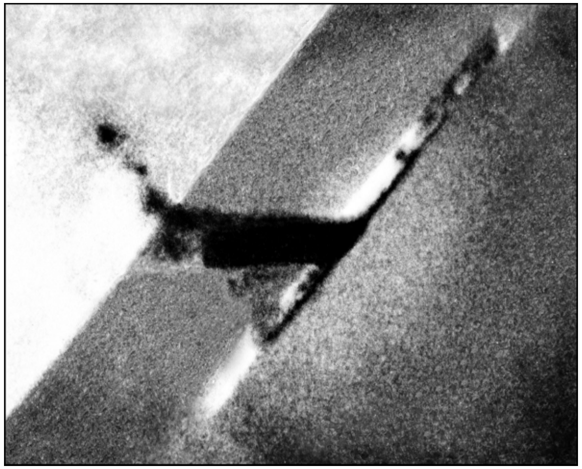


ARL & BAE Advanced Materials

Hot Isostatically Pressed Ceramic in Titanium Matrices



Titanium/Ceramic Preform before HIP



Dwell on Ceramic by Long Rod Penetrator

Post Impact Condition

Titanium Welding

—DETROIT ARSENAL—

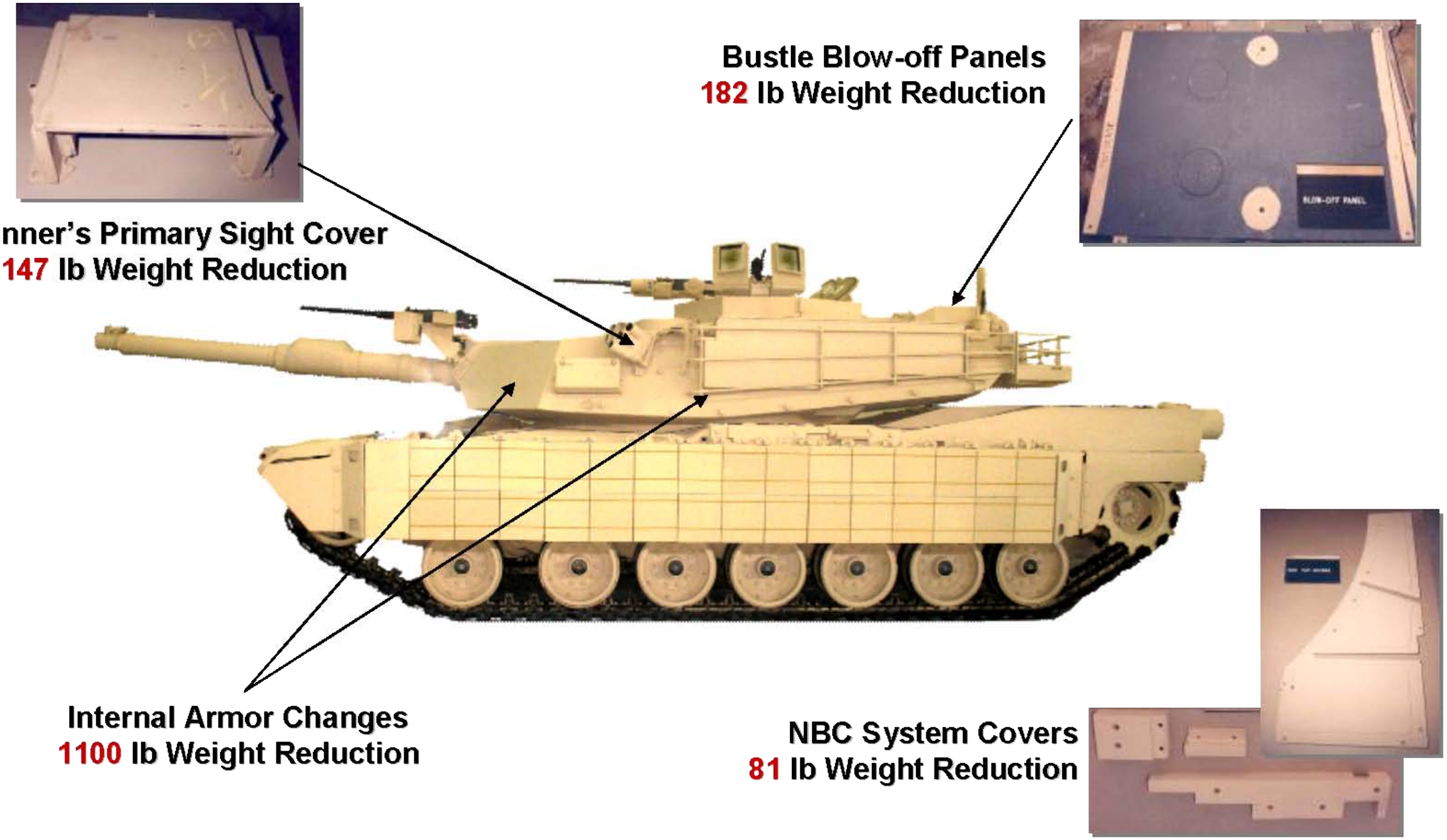
NEG. NO. 64132 DATE 7 Sept 60

Yes, that’s 1960

Titanium Welded Cab on ONTOS Vehicle

Current Applications

Titanium Weight Reduction Program for M1A2 Abrams Battle Tank



Gunner's Primary Sight Cover
147 lb Weight Reduction

Bustle Blow-off Panels
182 lb Weight Reduction

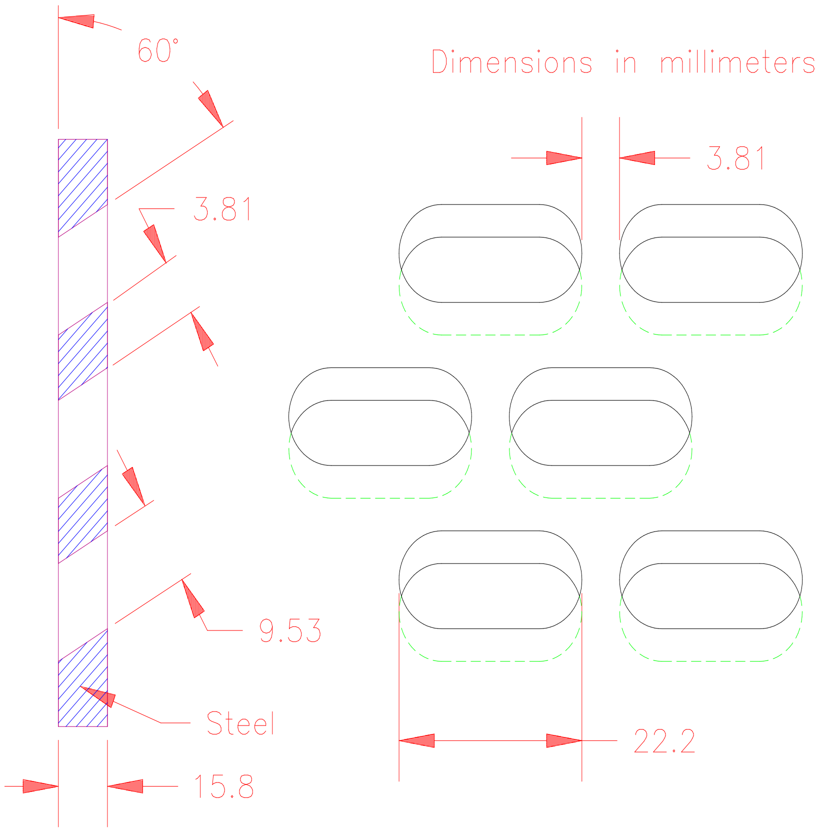
Internal Armor Changes
1100 lb Weight Reduction

NBC System Covers
81 lb Weight Reduction

GDLS >1500 lbs weight savings

Forged Commanders Hatch for M2A2 Bradley Fighting Vehicle

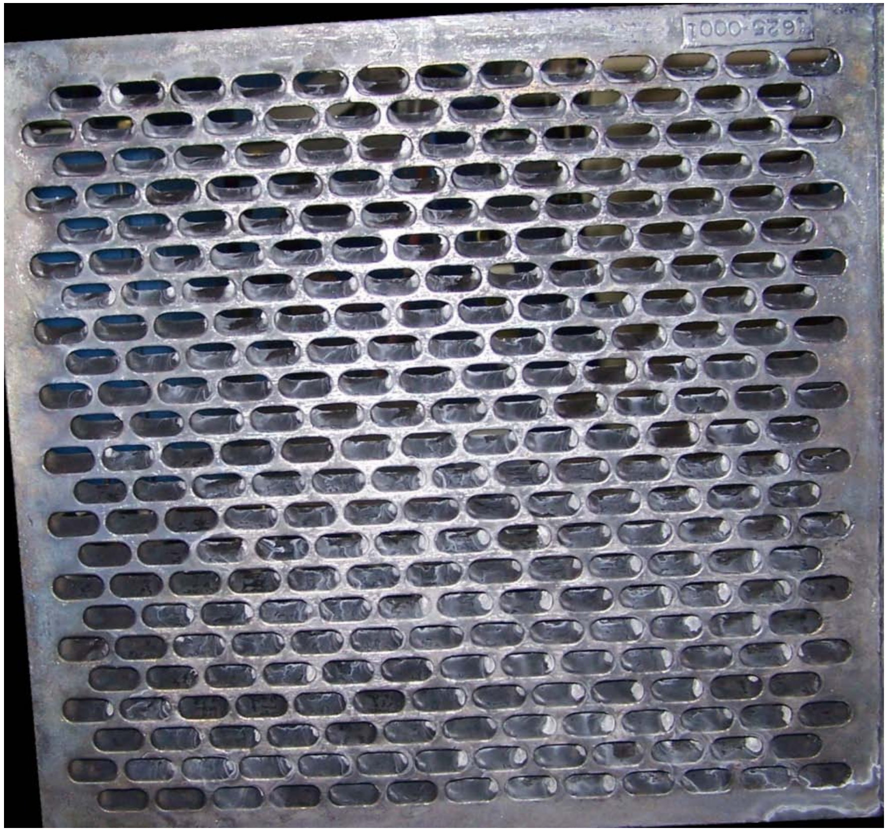
Steel P900 Tipping Plate Armors



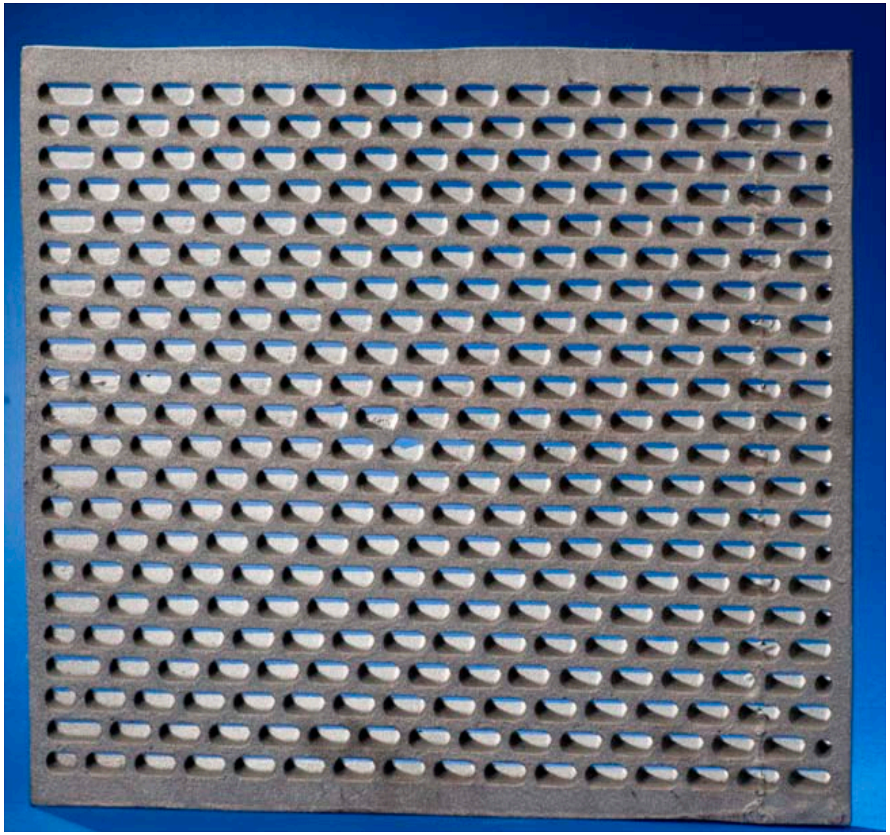
Cast P900 Tipping Plate Armor

X-ray of 14.5-mm Projectile Impacting a Single P900 Plate

New Application
Titanium P900 Armors



Pacific Cast Technologies
Cast P900 Titanium Plate



ATI Wah Chang Cast
P900 Titanium Plate

Current Applications

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

>7000lbs savings over M198

New Applications
Stryker Family of Vehicles

Titanium Commanders Cupola on RV and FSV Stryker Systems

Titanium Gun Pod on Stryker Mobile Protection Gun System

Courtesy – PM Stryker

Prototype Applications

BAE Pegasus Titanium Wheeled Prototype

Courtesy - BAE Santa Clara

Prototype Applications

Future Combat Vehicle Titanium Hull Prototype

BAE/TARDEC/ARL

Conclusions

- This presentation provided a cursory overview of the technical investigation of titanium for military ground applications.

- The written paper has expanded technical detail and references

- The main advantage of titanium relates to its lower density at equal or higher strengths than rolled homogenous armor steel of equal thickness.

- Military Specification MIL-DTL-46077G increased the thickness range and defined Class 3 and 4 alloys that provide equal protection at lower processing costs through increased oxygen levels, greater scrap content, advanced processing technology and reduced alloying.

- The development of Dual Hard titanium offers higher KE performance at equal weight and needs to be re-examined again.

Thank you