Titanium alloys have long been used for reducing system weight in aerospace 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 systems. The advantages of low density, high strength, a large competitive industrial base, and mature forming and shaping techniques make titanium an excellent choice for many military applications. The U.S. Army Research Laboratory has invested significant research efforts in understanding the material processing requirements for ground applications and this paper will provide an overview of that research. Major efforts have been investigating alternative alloys and amending existing military specifications to allow the use of alternative and lower cost alloys that meet specific ground applications.
THE DESIGN AND APPLICATION OF TITANIUM ALLOYS FOR US ARMY PLATFORMS

MILITARY PANEL

September 24, 2008

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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• Titanium was first investigated for armor use in 1950 by the Watertown Arsenal and Ti-6Al-4V became the main alloy of interest.

• The main advantage of titanium is the reduced density at high strength when compared with Rolled Homogeneous Armor (RHA) steel.

• Military Specification MIL-DTL-46077 sets the requirements for Ti-6Al-4V for armor applications. A large portion of this presentation will discuss recent revisions to this specification.

• This presentation will also examine some of the processing issues that impact on the use of titanium for ground platforms.

• The presentation will close with a brief overview of some current and proposed applications of titanium in military ground vehicles.
Titanium Alloys

**Alpha**
- CP Ti Gr 1-4
- 35-80 ksi
- \((0.18-0.40\% \text{ O}_2)\)
- Architectural
- Piping

**Alpha-Beta**
- Ti-6Al-4V
- 110-120 ksi
- Structures
- Armor

**Beta**
- Ti-10V-2Fe-3Al
- 170 ksi
- Torsion bars
- Springs

**Ductility, Weldability, Corrosion resistance, creep strength**

**Tensile strength, Density, Fabricability, Heat treatability**
### MIL-DTL-46077 Armor (Version F & G)

<table>
<thead>
<tr>
<th>Class</th>
<th>Chemistry</th>
<th>Max. O₂ Content</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>6AL- 4V</td>
<td>0.14%</td>
<td><strong>ELI</strong>-10% Elongation Min.</td>
</tr>
<tr>
<td>Class 2</td>
<td>6AL- 4V</td>
<td>0.20%</td>
<td><strong>Common Armor</strong> 6% Elongation Min.</td>
</tr>
<tr>
<td>Class 3</td>
<td>6AL- 4V</td>
<td>0.30%</td>
<td><strong>High Scrap Content</strong> Weld &amp; cold temp issues</td>
</tr>
<tr>
<td>Class 4</td>
<td>Not Limited</td>
<td>0.30%</td>
<td><strong>For future developments</strong></td>
</tr>
</tbody>
</table>

All 4 classes have the same min. strength and ballistic requirements.
<table>
<thead>
<tr>
<th>Thickness Ranges (inches)</th>
<th>Ballistic Test Projectile</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 to 0.615, excl</td>
<td>.30 cal. AP M2</td>
</tr>
<tr>
<td>0.615 to 1.575, excl</td>
<td>20mm FSP (Fragment Simulating Projectile)</td>
</tr>
<tr>
<td>1.575 to 1.950, excl</td>
<td>14.5mm API B32</td>
</tr>
</tbody>
</table>
| 1.950 to 4.000           | 20mm API-T M602
**Effect of Annealing Temperature**

**1.125" Ti-6Al-4V ELI plate**

**$V_{50}$ testing with 20mm FSP**

Charpy V-Notch Results

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

That’s why military armor specifications were developed.
## MIL-DTL-46077G
Ballistic Requirements

<table>
<thead>
<tr>
<th>Thickness Ranges (inches)</th>
<th>Ballistic Test Projectile</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125 to 0.249</td>
<td>To be determined</td>
</tr>
<tr>
<td>0.25 to 0.614</td>
<td>.30 cal. AP M2</td>
</tr>
<tr>
<td>0.615 to 1.574</td>
<td>20mm FSP</td>
</tr>
<tr>
<td></td>
<td>(Fragment Simulating Projectile)</td>
</tr>
<tr>
<td>1.575 to 1.949</td>
<td>14.5mm API B32</td>
</tr>
<tr>
<td>1.950 to 3.249</td>
<td>20mm API-T M602</td>
</tr>
<tr>
<td><strong>3.250 to 4.000</strong></td>
<td><strong>30mm APDS</strong></td>
</tr>
</tbody>
</table>

Quality has improved to the point where the 20mm can’t defeat some thicknesses!
• Beta processing can be controlled or avoided in wrought plate and forgings.

• Beta processing is unavoidable for welds, castings, and some powder metallurgy processes.

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

Yes, that’s 1960

Titanium Cab on ONTOS Vehicle
• Welds always perform worse than parent metal
• 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
Performance of Different Alloys

![Graph showing normalized V₅₀ limit velocity vs. 0.2% yield strength (ksi) for different alloys.](image)

- Ti-6-4 ELI
- Ti-6-4
- Ti-6-6-2
- Beta Alloys

- .30 cal. Ball M2
- .30 cal. FSP
Dual Hardness Titanium

Combine a hard and soft alloy together to improve performance.
Titanium Armor for Ground Vehicles

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

Steel used due to cost and availability issues.

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
Current Applications

Titanium Commander Hatch and Roof Applique on M2A2 Bradley Fighting Vehicle

Commander’s Hatch

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

>7000lbs savings over M198
Pegasus Titanium Wheeled Prototype
Future Combat Vehicle Titanium Hull Prototype

ARL & 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-DTL-46077G was discussed

• 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

• Requirements to reduce combat weights drives applications towards the lower density materials that have excellent ballistic properties

Thank you