Why Titanium? - Because vehicles always gain weight
Titanium in Combat Vehicles

- In the past, Titanium has been used in targeted, specific applications on several major weapons systems
  - Abrams, EFV, Bradley, Lightweight Howitzer
  - Almost Exclusively bolt on, non-structural applications

- The advantage of replacing armor steel with titanium has been, and remains, the ability to reduce vehicle structure weight to allow for better automotive performance and provide a weight margin for spiral upgrades to the system.
  - Armor Improvements
  - Electronics and Firepower
  - Non-traditional Survivability Upgrades
Titanium in Combat Vehicles

- Previous procurements used aerospace requirements
  - MIL-T-9046 specification material is expensive
  - Contains extensive material quality and testing requirements
    - Double or triple vacuum melting
    - Extensive Ultrasonic Inspection
    - Ultra low levels of impurities (i.e., Oxygen)

- Mil-46077 offers less expensive alternative with similar properties.
  - Multiple classes of material are allowed
    - Classes 1 through 4
    - Alloys other than Ti-6V-4Al are allowed
    - Oxygen allowable limits vary
    - Alternate melting practices allowed
  - Reduced requirements for material test and evaluation
  - Introduces a ballistic requirement not found in MIL-T-9046
“Classic” titanium fabrication utilized VAR processing to control composition and purity of ingot.
- Expensive process
  - Historical reliance on sponge instead of scrap input material
  - Requires multiple hard vacuums
  - Remelting procedures expensive in time and facility costs

- Historical military procurements used MIL-T-9046, not MIL-A-46077
  - No ballistic requirements
  - Detailed and costly QA requirements
  - High degree of control of impurities required use of VAR processing.
Electron beam (EBSM) and plasma arc (PASM) single melt processes yield similar products with similar quality and properties.
- Cast immediately to rectangular ingot --- facilitates subsequent rolling operations
- Economic due to high use of scrap
EBSM Produced Titanium Plate

- Single melt EBSM Ti-6Al-4V chemical composition and mechanical properties have been consistent and have met specification minimums throughout the Egyptian upgrade program
  - Chemical control of key alloy elements and impurities has been superb
  - Strength, ductility meet or exceed typical values obtained from traditional double melt stock
**Summary of TIMETAL 6-4 EBSM Chemical Analysis Results**

Red Vertical Lines Demarcate Individual Heats

Blue Horizontal Lines Demarcate Specification Limits

**Variations in Al content can occur at the start of a melt. These areas are always cropped from final product.**
Summary of TIMETAL 6-4 EBSM Chemical Analysis Results
Red Vertical Lines Demarcate Individual Heats
Blue Horizontal Lines Demarcate Specification Limits

EBSM Titanium Plate: Vanadium Content

Vanadium Content (%) vs. Cumulative Weight (lb)

GENERAL DYNAMICS
Land Systems
Summary of TIMETAL 6-4 EBSM Chemical Analysis Results

Red Vertical Lines Demarcate Individual Heats
Blue Horizontal Lines Demarcate Specification Limits

EBSM Titanium Plate: Oxygen Content

Intentionally manufactured as ELI.
Intentionally manufactured at reduced oxygen level.
## EBSM Titanium Plate: Chemistry

<table>
<thead>
<tr>
<th>Element, Wt %</th>
<th>CN1632 Top</th>
<th>CN1632 Bottom</th>
<th>CN2348 Top</th>
<th>CN2348 Bottom</th>
<th>Specification [1]</th>
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<tbody>
<tr>
<td>Aluminum</td>
<td>6.08</td>
<td>6.11</td>
<td>6.20</td>
<td>6.27</td>
<td>5.50 - 6.75</td>
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<tr>
<td>Vanadium</td>
<td>3.96</td>
<td>4.00</td>
<td>4.03</td>
<td>4.02</td>
<td>3.50 - 4.50</td>
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<td>Iron</td>
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<td>0.15</td>
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<td>Oxygen</td>
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<td>0.18</td>
<td>0.18</td>
<td>0.17</td>
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<tr>
<td>Carbon</td>
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<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
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<tr>
<td>Nitrogen</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>---- - 0.05</td>
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<tr>
<td>Tin</td>
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<td>0.02</td>
<td>0.03</td>
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<td>Zirconium</td>
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<tr>
<td>Copper</td>
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<td>Nickel</td>
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<td>Silicon</td>
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<td>Total Residuals</td>
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[1] AMS 491, AMS-T-9046, MIL_T_9046

[2] Determination not required for routine acceptance
# EBSM Titanium Plate: Mechanical Properties

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<tr>
<th>Heat</th>
<th>Orien</th>
<th>UTS</th>
<th>0.2% TYS</th>
<th>RA</th>
<th>ELONG</th>
<th>KIC</th>
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<tr>
<td></td>
<td></td>
<td>ksi</td>
<td>MPA</td>
<td>ksi</td>
<td>MPA</td>
<td>%</td>
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<td>Required Min:</td>
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<td>120</td>
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<td>T</td>
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<td>T-L</td>
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<td>T-L</td>
<td>64.7</td>
<td>71.1</td>
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</tr>
</tbody>
</table>
**EBSM Titanium Plate: Fatigue Properties**

- **EBSM titanium displays classic fatigue crack growth characteristics**
  - $R = 0.05$ data on EBSM material tracks historic $R = 0.10$ design data perfectly.
  - Equivalent fatigue threshold to classic MIL-HBK design guides
  - Data at higher mean stress levels (i.e., higher $R$ ratio is being developed)
  - Crack growth was ‘well behaved’
EBSM Titanium: Ballistic Performance

- Initial small caliber plate acceptance ballistic data has met all MIL-A-46077 required V50 limits.
  - Data is consistent with historical data base for conventional double melt product.
    - 0.30 cal AP (0° obliquity)
    - 0.50 cal AP (0° obliquity)
    - 14.5 mm AP (0° obliquity)
    - 20 mm AP (0° obliquity)
  - Performance against Fragment Simulating Projectiles is in process
    - Previous work indicates that Fragments are a challenging threat for titanium.
    - In many cases the requirement to defeat Fragments drive the armor design and/or necessitate spall liners
    - 20 mm FSP (0° obliquity) is planned
Titanium Utilization - M2 Bradley

- Bradley Commanders Hatch
  - First ever production use of Ti-6Al-4V (forging)
Titanium Utilization - EFV (fielded or candidates)

- Hydrodynamic Suspension Forgings 6-4
- Gun Cradle
- Lifting Eyes
- Idler Wheel
- Track tensioner
- Arm & Cylinder
- Sprocket Wheel
Titanium Utilization - Lightweight Howitzer

Gun Supports

Gun Mount
Titanium Utilization - Crusader
Titanium Utilization - M1 Abrams

- All indicated parts were prototyped and tested.
- Only blow-off panels and GPS GPS cover were fielded.
Titanium in Combat Vehicles

- Future Combat System (FCS) currently is evaluating the structural requirements, survivability, and manufacturability of candidate materials for use as primary structure for common, and variant specific areas of the FCS system
- Structural Candidate Materials include:
  - Titanium (mainly Ti-6Al-4V)
  - High strength aluminum (2519, 2195)
  - “Classical” Al Armor (5083)
  - Polymer based composites
Titanium Utilization - M1 Abrams (Egypt)

- First large scale production use of Cold Hearth Single Melt Titanium (MIL-DTL-46077, class 2)
  - Plate form (Electron Beam Single Melt process: EBSM)
  - Turret structural components
  - Material properties have been excellent
  - Thickness range of 2.0” – 3.0”

- Low cost Ti is the key to future use of Ti alloys in combat vehicles
  - Fewer spec requirements
  - Lower material costs
  - MIL-DTL-46077, not MIL-T-9046
ESBM in BCT Strykers

- Titanium’s excellent performance in previous vehicles led to its use as an armor material in the Stryker vehicle platform
- Most widely used as armor components in the Stryker Mobile Gun System (MGS)
  - MGS is a “shooter” variant which carries a 105mm main gun, autoloading capabilities and a crew of three.
  - Combat use of the MGS is to provide direct fire support to ground combat forces.
Titanium Armor on MGS

Gun Pod
- Welded titanium armor plate
- EBSM MIL-A-46077
- Used as stand alone armor and as part of more complex recipes

Turret Side
- First use of a ring rolled titanium forging as an armor material ring rolled material
- Forms the base structure for the turret
Conclusions

- All evaluations so far have shown that the ballistic protection and mechanical properties provided by Ti-6Al-4V EBSM are indistinguishable from that of conventional aerospace Ti-6Al-4V.

- This indicates that the material performance is dictated by chemical composition and thermo-mechanical processing rather than by the original melt method.

- The incremental cost reduction provided by the use of Ti-6Al-4V EBSM should enable additional weight reduction in existing and future combat vehicles.
Single Melt Titanium: Path Forward

- **Single Melt Titanium wrought products are the future for military use of Titanium on future combat vehicle platforms.**
  - Electron Beam and Plasma Arc single melt processes available
    - Physical, chemical and mechanical properties are excellent
  - Single melt Titanium is already in production use by GDLS on the Egyptian tank program and Stryker program.
    - Mechanical, physical and ballistic performance of rolled plate product has been excellent, and has been shown to be equivalent to plate made with VAR double/triple melt processing.
  - Single melt material offers significant cost savings, on a per pound basis, when compared to typical aerospace grade materials.

- **Weldability trials need to be conducted**
  - No problem is expected since chemical composition and microstructure of EBSM plate is identical to current production grades of Titanium

- **Continued evaluation/development of forgings and ring rolled product as armor material.**