Solid State Processing of New Low Cost Titanium Powders Enabling Affordable Automotive Components

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Outline

• Introduction
• Potential Applications for Titanium in the Automobile
• Armstrong Process/ITP Powder
• Early Studies Demonstrating Mechanical Properties of Low Cost Powder
  - Vacuum Hot Pressing (VHP)
  - Extrusion
• Development of Economical Solid State Processing of “Low-Cost” Ti Powders
  - Cold Isostatic Pressing Followed by Pneumatic Isostatic Forging (CIP/PIF)
  - Roll Compaction
• Conclusions/Future Work

Titanium Plates Hot Pressed from ITP’s Low Cost Titanium Powder
Introduction

• Ti Offers Attractive Properties.
  – High Specific Strength.
  – Good Elevated Temperature Properties.
  – Excellent Corrosion Resistance.
  – Allows for Damage Tolerant Design.

• Cost and Availability Rising Concern
  – Lead Times Up to a Year
  – Plate Prices of $40 to $50/Lb

• Cost Limits Application to Specific Markets.

• New Low Cost Titanium Powders Could Initiate a Paradigm Shift in Titanium’s Use in Industry, Including Automotive

Heat Exchangers
http://www.titanmf.com

Biomedical - Knee Replacement

787 Boeing
http://www.boeing.com/commercial/787family/index.html

Land Combat Systems - Pegasus
BAE Systems

Introduction
Titanium in the Automobile

- Wide Range of Various Titanium Automotive Components Possible
  - Outside of Engine: Springs, Body Components, Brake Rotors, Bumper Supports, Muffler, Drive Shafts, Etc.
  - Engine: Turbo Charger Compressor Wheels, Turbine Wheel, Intake and Exhaust Valves, Connecting Rods, Piston Crown and Pin, Push Rods, Rocker Arms and Shaft, Camshaft, Valve Spring, Retainer and Rotater

- E.G., Recent Study at ORNL Studied Light Weight Materials to Replace Cast Iron in Diesel Engines
  - Analyzed Replacing Grey Cast Iron to Ti-6Al-4V in the engine head and blocks
  - Increasing the “Power of the Engine by 50% while reducing the weight by 15%” FY2005 Progress Report, DOE-Heavy Vehicle Propulsion Materials

- However, Titanium’s Cost Prevents Penetration Into the Automotive Market
Titanium Production

- 1998 U.S. Production (Million Metric Tons).
  
  Steel: 99

  Al: 7.2

  Mg: 0.14

  Ti: 0.05


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<tr>
<th>Item</th>
<th>Material ($/lb)</th>
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<tr>
<td></td>
<td>Steel</td>
</tr>
<tr>
<td>Ore</td>
<td>0.02</td>
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<tr>
<td>Sponge</td>
<td>0.10</td>
</tr>
<tr>
<td>Ingot</td>
<td>0.15</td>
</tr>
<tr>
<td>Sheet</td>
<td>0.30-0.60</td>
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Faller, K. Froes F.H. JOM April 2001. pp.27

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- Titanium
  - 9th Most Abundant Element
  - 4th Most Abundant Structural Metal
  - 0.6% of Earth’s Crust

- Cost/Use of Ti Not Reflective of Abundance

- Current Synthesis Technology 50 Years Old

- Basic Research into Lower Cost Refining and Processing Remains Critical

- Integrated Approach Synthesis to Final Product

- DTi, “Low-Cost” Ti Powders
  - International Titanium Powder
  - MER/Dupont
Conventional Technology Compared to DARPA Funded Armstrong Process

- **Kroll Process**
  - Mg Reduction of TiCl$_4$
  - Batch Process
  - Requires Acid Leaching and Vacuum Arc Remelting
  - Finally Milled into Desired Product
  - PM Approach Not Attractive for Many Applications, Price Above $50/lb

- **Armstrong (ITP) Process**
  - Reduction of TiCl$_4$ in Na Liquid Loop
  - Continuous Process
  - Ability to Produce Prealloyed Powder
  - Cost of Powder $5-8/lb
  - PM Approach Economically Attractive
  - Thousands of Pounds of Powder Have Been Produced
International Titanium Powder (ITP), Armstrong Process Titanium Powder

- New 4 Million Pound Titanium Plant Under Construction in IL
- Chemical Analysis of Powder Has Fallen within Specification
  - Grade 2 for CP Ti (e.g., 0.12 to 0.21 wt. % O)
  - Grade 5 for Ti-6Al-4V
- Energy Consumption for Reduction Process
  - 50 Year Old Conventional Kroll Process = 355 MBtu/ton
  - Armstrong Process = 165 MBtu/ton
  - A 53.4% Reduction in Energy Consumption.
- “Low Cost” Powder Allows for:
  - Economical Solid State / PM Processing
  - Near Net Shape Consolidation
  - Compositing and Layered or Engineered Structures
  - Ability to Use Beneficial Elements Not Possible in Conventional Processing (E.g., Small Additions of Boron Have Greatly Increase Fatigue Lifetime of Titanium Alloys)
Processing – Cost Break Down of Fabricating 1” Ti Plate

- ITP “Low Cost” Ti Powders Developed in DTi Program Address 25% of 1” Plate Fabrication Costs
- The Secondary Processing or Processing into Finished Product (62% VAR and Milling) Needs to Be Addressed
- Conventional Milling Operations, Scrap Generated: 40 to 60%
- PM Approach with ITP Powder Ability to Reduce Scrap to Less Than 10%

Cost Break Down to Produce 1” Thick Titanium Plate Using Kroll – VAR Melted Titanium
Development of Multiple PM Processes for Economical Product

Near Net Shapes
Hot Pressed, Forged, Press+Sinter

Plate
Forged, PIF, Hot Roll, HIP

Bars and Rod Extrusion

Sheet
Roll Compacted

Powder
Vacuum Hot Pressing (VHP) of ITP CP Ti and Ti-6Al-4V – Plate and Near Net Shape Production

- Armstrong Ti and Ti-6Al-4V powder were vacuum hot pressed.
- Interstitial Levels of ITP CP Ti, VHP Produced Plate within Specification
- Mechanical testing, microstructures, and chemical analysis comparable to conventional wrought properties.

<table>
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<tr>
<th>Sample</th>
<th>YS [MPa]</th>
<th>UTS [MPa]</th>
<th>Ductility [%]</th>
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<tbody>
<tr>
<td>ITP VHP CP Ti 900°C/30min</td>
<td>517</td>
<td>617</td>
<td>20.7</td>
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<tr>
<td>CP Ti Grade 2</td>
<td>345</td>
<td>448</td>
<td>20.0</td>
</tr>
<tr>
<td>ITP VHP Ti-6Al-4V 950°C/60min</td>
<td>963</td>
<td>994</td>
<td>13.8</td>
</tr>
<tr>
<td>Ti-6Al-4V Grade 5</td>
<td>828</td>
<td>897</td>
<td>10.0</td>
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Ti Processing – Extrusion

• Mechanical testing and microscopy

ORNL, 1250 ton - extrusion press

Extruded CP Ti
Tensile Bars

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<tr>
<th>Sample*</th>
<th>YS [MPa]</th>
<th>UTS [MPa]</th>
<th>Ductility [%]</th>
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<tr>
<td>Extruded Ti</td>
<td>407</td>
<td>552</td>
<td>17.0</td>
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<tr>
<td>Ti Grade 2</td>
<td>345</td>
<td>448</td>
<td>20.0</td>
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</table>

* Insufficient Ti-6Al-4V powder was available at the time of initial extrusion demonstration. Recent increase in ITP Ti-6Al-4V powder production will enable ORNL to produce Ti-6Al-4V extrusions and test bars in the near future.
Development of Cold Isostatic Pressing / Pneumatic Isostatic Forging (CIP/PIF) Process

- Necessity for Cost Effective Method of Producing Plate and Near Net Shape Components
- PIF AMETEK Patented Process – Rapid Gas Pressurization (1 to 2 Minutes)
- Very Preliminary CIP/PIF Work Performed with AMETEK Shows Promising

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<tr>
<th>Description</th>
<th>VHP</th>
<th>CIP/PIF</th>
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<tbody>
<tr>
<td>% of Theoretical Density</td>
<td>99.4%</td>
<td>99.6%</td>
</tr>
<tr>
<td>Oxygen Pickup (wt. %)</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>Microstructure</td>
<td>Equiaxed</td>
<td>Equiaxed</td>
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<tr>
<td>Hardness (VHN)</td>
<td>343 +/- 31.9</td>
<td>346 +/- 27.3</td>
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Roll Compaction of Armstrong (ITP) Derived Ti Powders

- Collaborative Effort Between ORNL and AMETEK to Develop Roll Compaction Manufacturing Technology for Low Cost Titanium Powders
- Both Commercially Pure Ti and Ti-Al-V Alloys Have Been Roll Compacted
- ITP Powder Has Resulted in:
  - Green Densities of 60 to 70%
  - Sheet Widths of 15” (or Greater)
  - Coils of 28’ in length have been produced with no binders required.
  - Initial Studies Performed on Thin Sheet (0.02”), But Projections Indicate Thicknesses at 0.1” or Higher Are Possible with Large Roll Diameters
- Solid State Sheet Processing After Roll Compaction: Sinter, Cold Roll, And Anneal Lead to Fully Consolidated Sheet (>99%)
- Initial Trial Resulted in High Strength/Low Ductility Due to High Oxygen
- However, Further Development Has Led to Acceptable Oxygen Levels: 200ppm Pickup or Less During Roll Compaction, and Less Than 800ppm Pickup After Full Consolidation – Mechanical Testing Ongoing

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Conclusions

• Low Cost Titanium Powders Are Now Produced That Could Cause a Paradigm Shift in the Use of Titanium for Automotive Applications.
• Further Development in Powder Metallurgy or Solid State Consolidation of the New Titanium Powders Is Required to Realize the Most Economical Components and Penetrate the Automotive Industry.
• Vacuum Hot Pressed Plates and Extruded Bar of the Low Cost Titanium Have Been Produced with Tensile Properties that Meet ASTM Specifications.
• Oak Ridge National Laboratory Is Currently Collaborating with Industry to Develop Economical Processes to Produce Plate, Sheet, Bar/Wire, and Net Shape Components.

Future Work

• Further Development of Existing Work Shown Today
  • Comprehensive Mechanical Properties (Fatigue)
  • Other Low Cost Powders as Available
• Development of Other Solid State Technologies (e.g., Upset Forging, Press+Sinter)
• Current Program to Produce and Join Plates for Military Application
• Further Collaboration with Industrial Partners to Allow for the Penetration of Titanium Into New Markets Is Invited