POWDER METALLURGY AND SOLID STATE PROCESSING OF ARMSTRONG TITANIUM AND TITANIUM ALLOY POWDERS

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Introduction

- Ti Offers Many Attractive Properties.
  - High Specific Strength.
  - Good Elevated Temperature Properties.
  - Excellent Corrosion Resistance.
  - Allows for Damage Tolerant Design.
- Cost and Availability Are a Concern
  - Lead Times 12 to 18 Months
  - Plate Prices of $35 to $50/Lb
- Cost Limits Application to Specific Markets.
- Critical Need for Basic Research into Lower Cost Refining and Processing
- New Low Cost Titanium Powders Could Initiate a Paradigm Shift in Titanium’s Use in Industry
- Oak Ridge National Laboratory is Working with Industry to Develop the Necessary PM Technologies to Consolidate the New Low Cost Ti Powders
Conventional Technology Compared to DARPA Funded Armstrong Process

- **Kroll Process**
  - Mg Reduction of TiCl₄
  - Batch Process
  - Requires Acid Leaching and Vacuum Arc Remelting
  - Finally Milled into Desired Product
  - PM Approach Not Attractive Except for Specialty Components

- **Armstrong (ITP) Process**
  - Reduction of TiCl₄ in Na Liquid Loop
  - Continuous Process
  - Ability to Produce Prealloyed Powder
  - Price of Powder Competitive with Kroll Sponge
  - 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, U.S.
- 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
- Typical Powder Particle Size Range: 150 to 2000 µm with a mean size of 400 µm
- Energy Consumption for Reduction Process
  - Armstrong Process = 165 MBtu/ton
  - A 53.4% Reduction in Energy Consumption.
- “Low Cost” Powder Allows for:
  - 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)
**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

- **Low Cost Ti 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>
<thead>
<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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</table>
Fatigue Testing Procedure for VHP Ti-6Al-4V Plate

- Ti-6Al-4V ITP Powder Pressed at 1,050°C, 1 hour in Vacuum
- Initial powder had slightly high oxygen compared to ASTM Grade 5 (O₂ ~ 0.23 wt. %).
- Consolidated Plate: O₂ ~ 0.25 wt. %, 200 ppm pickup
- Hot Rolled VHP Plate (850°C, 50% reduction)
- Round Bar Specimen with 1/8" testing diameter, less than half hot rolled gauge thickness
- R ratio, s_{min}/s_{max} = 0.1
- Frequency = 10 Hz
Ongoing Fatigue Results

- Preliminary Results of Specimens Taken Normal to Rolling Direction Indicate ITP VHP Ti-6Al-4V Samples Are Comparable to Conventionally Pressed and Forged Powders

DTi “Low-Cost” Ti-6Al-4V Plates Show Comparable Ballistic Results to Conventional Wrought Plate

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- VHP Consolidated Plate (950°C and 1,050°C)
- Ballistics testing performed at BAE Systems using MIL-DTL-46077G spec.
  - 0.30 cal APM2 (same as 7.62mm AP).
  - Velocity increased until 0.5” plate was penetrated.
- 1,050°C Plate - Estimated $V_{50} \approx 2,037 \text{ fps}$, within 2% of conventional wrought Ti-6Al-4V properties for specific thickness of plate (ref: MIL-DTL-46077 spec).
  - No cracking.
  - Good deformation/ductility (note: #4, Back).
  - Extremely limited spalling.
- 950°C Plate – Estimated $V_{50} > 2,097 \text{ fps}$, within 0.3% of specification for specific plate thickness WITHOUT penetration. V50 test could not be completed due to insufficient test area.
- Low-cost Ti-6Al-4V plate exhibited comparable performance to wrought plate.
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 Promise
- Ballistic Results Have Been Comparable to Wrought Plate
- Mechanical Evaluation Ongoing

<table>
<thead>
<tr>
<th>Description</th>
<th>VHP</th>
<th>CIP/PIF</th>
</tr>
</thead>
<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>
</tr>
<tr>
<td>Hardness (VHN)</td>
<td>343 +/- 31.9</td>
<td>346 +/- 27.3</td>
</tr>
</tbody>
</table>
Ti Processing – Extrusion

- Mechanical testing and microscopy

ORNLE, 1250 ton extrusion press

Extruded CP Ti Tensile Bars

As-extruded Ti

Tensile Bars

Sample* | YS [MPa] | UTS [MPa] | Ductility [%]
---|---|---|---
Extruded Ti | 407 | 552 | 17.0
Ti Grade 2 | 345 | 448 | 20.0

* 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.
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) and Proof of Continuous Production (Coils of 28’ in length)
- 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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Results of ITP Ti Press+Sinter

- ITP CP Ti and Ti-6Al-4V Powders
  - Pressed to Pressures of 100 ksi
  - Sintered at Temperatures 1,100°C and 1,300°C
- Densities for given loads and temperatures:
  - Up to 90% theoretical for CP Ti
  - Up to 95% theoretical for ITP Ti-6Al-4V
- < 300 to 400 ppm pickup in oxygen
- Further Work in Progress
Conclusions

• Low Cost Titanium Powders Are Now Produced That Could Cause a Paradigm Shift in the Use of Titanium for Industry and Other Applications.
• Further Development in Solid State Consolidation of the New Titanium Powders Is Required to Realize the Most Economical Components and Penetrate New Markets.
• Vacuum Hot Pressed Plates and Extruded Bar of the Low Cost Titanium Have Been Produced with Tensile Properties that Meet ASTM Specifications.
• Very Preliminary Ballistic and Fatigue Results are Encouraging.

Future Work

• Further Development of Existing Work Shown
  • Comprehensive Mechanical Testing for Various PM Approaches (CP Ti, Ti-6Al-4V)
  • PM Development of Other Low Cost Powders as Made Available
• Currently Fabricating 200lb Military Component from ITP Powders
• Welcome Any Further Collaboration to Allow for the Penetration of Titanium Into New Markets

Heat Treatment and Rolling of Ti-6Al-4V Plates for 200lb Military Component
Acknowledgements

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  – Taras Lyssenko

Questions?