Forging of Powder Metallurgy Processed Ti-6Al-4V

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FAST (Forging of Affordable Solid-state Titanium) Project Description – Phase 1

- **Goal:** Improve the buy-to-fly ratio and reduce the number of forging steps in a multi-phase project

- **Team:** Oak Ridge National Laboratory, Lockheed Martin, and Wyman-Gordon

- **Phase 1 Objective:** Demonstrate forged component using Ti-6Al4V powder
  - consolidate Ti alloy powder in the solid state to form a billet and forge in production press
  - measure the properties of the forging and compare to existing specifications for forged Ti-6Al-4V

- **Deliverables:** forged parts, property data, and a final report
**ORNL’s Role in US Titanium Powder Metallurgy R&D**

- **United States Titanium Market Heavy on Aircraft Applications**
  - United States: Last 5 years, ~75% of titanium metal used in aerospace applications
  - New Aircraft Platforms Buy to Fly Ratio Closer to 10 to 1

- **Need for Energy- and Material-Efficient Manufacturing**
  - New Reduction Processes Result in Powder/Particulate
    (Armstrong Process® Powder, CSIRO, ADMA, UTRS, MER, Metalysis, etc.)
  - Developments in Existing Powder Production
    - Hydride-Dehydride
    - Plasma Rotated Electrode Powder
  - ORNL Develops Process Methodologies to Consolidate Titanium Powders Into
    - Net Shape Components Utilizing Powder Metallurgy or Additive Manufacturing Technologies.
    - Sheet / Thin Gauge Components from Roll Compaction

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**Process Energy Demands to produce a 2,200 pound Aero Component**

<table>
<thead>
<tr>
<th></th>
<th>Kroll</th>
<th>Max of 5 PM Routes</th>
<th>Min of 5 PM Routes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine / anneal</td>
<td>297</td>
<td>34</td>
<td>25</td>
</tr>
<tr>
<td>Reduction</td>
<td>1690</td>
<td>573</td>
<td>248</td>
</tr>
<tr>
<td>Total Energy</td>
<td>1987</td>
<td>607</td>
<td>274</td>
</tr>
</tbody>
</table>

Process energy demands to produce one metric ton of finished aero components from Ti-6Al-4V comparing a 2:1 buy to fly ratio for powder metallurgy and 10:1 for conventional processing based on current machining practices.
Current Ti PM & Additive R&D at ORNL

Die Press

Cold Isostatic Press → Sinter

Hot Isostatic Press (HIP)

Vacuum Hot Pressing (VHP)

Pneumatic Isostatic Forge (PIF)

Extrusion

Forging

Additive Manufacturing

Roll Compaction

Near net shape components

Sheet products

Armstrong

HDH

PREP

Alloy and CP

ITP powder

HDH powder

Powder attrition (milling process) and Classification

Powder Characterization

Consolidation Modeling

Sintering Behavior

Microstructure

Mechanical Properties
Benefits to Proposed Approach

- Utilize new powders and new technologies to improve costs and efficiencies
- Benefits include:
  - Improved availability through increase in U.S. suppliers and better efficiency with material (Supply stream could be separate from current titanium stream)
  - Dramatically reduced scrap by decreasing machining operations (e.g., 14:1 down to 7:1 on average)
  - Lower cost of parts

Example: Material loss in producing long aircraft component forging.
Preliminary Upset Forging Tests with Two Powders

Armstrong Ti-6Al-4V (High Nitrogen) Canless HIP or PIF Billet

Hydride-Dehydride Ti-6Al-4V Vacuum Hot Press Billet

Forging

Forged Pancakes

Microstructure
Fabrication of a Powder Preform for Experiment

PREP Ti-6Al-4V Powder

Hot Isostatic Press to Full Density
Bodycote IMT, Inc., Andover, MA

Machine Billet
Peak Manufacturing, Sterling, MA

Forged Component Before Machining
(Multiple Steps)
Wyman-Gordon, Grafton, MA

A ~300 lb. Machined Billet
Makes 2 ~10 lb. Components

Buy-to-Fly Ratio = 14:1
Powder Forges Like Conventional Preform

Open Die Forging

Closed Die Forging

Powder Metal

Wrought Metal

Powder Metal

Wrought Metal
Property Measurements Performed

- Chemical and Mechanical Testing:
  - Tensile Strength – ASTM E8
  - Fracture Toughness – ASTM E399-09
  - Crack Growth – ASTM E647-08
  - Strain Life Fatigue – ASTM E606-04
  - Hydrogen Analysis – ASTM E1447
  - Additional tests included stress corrosion, macroscopic, microstructure, and alpha casing per Lockheed Internal Specifications

<table>
<thead>
<tr>
<th>Chemical Composition Comparison</th>
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<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>ASTM B381 F-5</td>
</tr>
<tr>
<td>ASTM B381 F-29</td>
</tr>
<tr>
<td>PREP</td>
</tr>
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Oxygen content of forged component was 0.18%.
No evidence of an alpha case was seen with PM processing.

Typical microstructure of PM Ti-6-4 had an average grain size <200 microns.

Typical wrought Ti-6-4 ELI has an average grain size 1.5 to 7 times greater.
Fracture Toughness

Fracture toughness values were 11% lower for PM than conventional process. This is attributed to finer grain structure and/or higher oxygen of initial powder.

Stress Corrosion

Stress corrosion values were 17% lower for PM than conventional process.

Development of beta anneal process suitable for PM beta-forged components and lower oxygen in feedstock would improve toughness.

<table>
<thead>
<tr>
<th>Sample</th>
<th>% Increase in Time to Failure</th>
<th>% Increase in $N_f$ Cycles</th>
<th>% Increase in $N_i$ Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL1 (Lowest)</td>
<td>58</td>
<td>59</td>
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</tr>
<tr>
<td>SL2</td>
<td>30</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>SL3 (Highest)</td>
<td>11</td>
<td>12</td>
<td>11</td>
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Strain Life Fatigue

% Improvement in Performance of PREP Ti-6Al-4V Powder Metal Compared to Wrought ELI Plate

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Transition to Production

• Direct path to implementation:
  – The complete supply chain was represented
    • Powder supplier
    • Hot isostatic pressing
    • Forging
    • Equipment supplier (Lockheed Martin)
  – Validation testing of forged powder components from supply chain was included as part of this demonstration project

• Next Phase
  – Evaluation of multiple powder feed stocks to lower cost
  – Powder metallurgy versus additive manufacturing
  – Preform closer to near net shape article (14:1 down to X:1, where X is 5, 6, or 7)
  – Determination in the total reduction in forging steps
  – Joining evaluation
  – Qualification and certification

### Evaluation of Multiple Powders

<table>
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<th>Armstrong® Powder</th>
<th>Theoretical Density, %</th>
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<tbody>
<tr>
<td></td>
<td>Press and Sinter*</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>96.8-99.6</td>
</tr>
<tr>
<td>CP-Ti</td>
<td>83.1 - 84.9</td>
</tr>
</tbody>
</table>

* CIPed at 50 ksi + sintered at 1200 - 1300°C/1h,
**HIPed at 950°C/15ksi/4h without can

### Cold Spray Net Shape Components

- Source: [www.arl.army.mil](http://www.arl.army.mil), ARL Center for Cold Spray

- No Can Used in HIPing

- Laser Deposited
  - Net Shape
Discussion

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