Next-Generation Development of a Superior Grade Titanium Ti-6Al-4V Alloy via Oxygen Solid Solution Strengthening for Aerospace & Defense Applications

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High Performance and Cost Effective P/M Titanium Materials

All materials strongly requires:

✓ Higher Performance
✓ Stable Supply in the world
✓ Cost Reduction

Advance P/M pure Titanium in this study:

✓ Ubiquitous elements (O, N, C, H)
✓ No use of rare metals
✓ Direct-use of cheaper TiH₂ powder

Hydration

Dehydration

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Fundamentals for Cost-Performance Improvement of P/M Titanium

- Direct use of TiH$_2$ powder to fabricate P/M pure titanium materials
- Strengthening of titanium by carbon, nitrogen and oxygen
- High-strength pure titanium material using TiH$_2$+TiO$_2$ mixed powders
Direct Use of TiH$_2$ Powders by Sintering and Hot Extrusion

TiH$_2$ green compact
(Relative density; 82%)

Consolidation with $P=600$ MPa pressure at room temperature

$\text{TiH}_2$ powder compact

Fragmentation & Interlocking

$\text{Ti}$ powder compact

Plastic deformation
Direct Use of TiH₂ Powders by Sintering and Hot Extrusion

Decomposition behavior of TiH₂

TiH₂ = TiHₓ + H₂ [x = 0.7~1.1]  (1)

TiHₓ = α-Ti + H₂  (2)

Sintered at 800~1000 °C for 3hrs
(argon gas flow; 3 litter /min)

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Successful Fabrication of P/M Ti Material Using TiH₂ Powders

TiH₂ powder compact
Sintered at 800~1000°C
Hot extrusion at 800°C

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Strengthening of Titanium by Carbon, Nitrogen and Oxygen

Carbon Nanotube (CNT) reinforcements for titanium powder materials

Fractured surface after tensile test

In-situ formed TiC

Strengthened by CNT/TiC dispersion & Carbon solid solution
Strengthening of Titanium by Carbon, **Nitrogen** and Oxygen

Pure Ti powders heated in N₂ at 600C ⇒ Compact & sintering ⇒ Extrusion

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Ti</td>
<td>484.3</td>
<td>653.9</td>
<td>29.0</td>
</tr>
<tr>
<td>Ti-N₂-600C-1h</td>
<td>903.7</td>
<td>1008.2</td>
<td>24.8</td>
</tr>
<tr>
<td>Ti-N₂-600C-2h</td>
<td>1080.1</td>
<td>1146.8</td>
<td>11.1</td>
</tr>
</tbody>
</table>

- Nitrogen solid solution into Ti
- No formation of TiN brittle phase
- Good balance between stress/elong.

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Oxygen Solid Solution Strengthening of P/M Titanium Material

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![Graph showing the relationship between additive TiO$_2$ content and mechanical properties of pure Ti matrix.](image)

<table>
<thead>
<tr>
<th>TiO$_2$ content (mass%)</th>
<th>Grain size / $\mu$m</th>
<th>$\Delta$ 0.2% YS by grain refinement / MPa *</th>
<th>0.2% YS (revised) / MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11.6</td>
<td>0</td>
<td>437.7</td>
</tr>
<tr>
<td>0.6</td>
<td>9.3</td>
<td>19.9</td>
<td>627.4</td>
</tr>
<tr>
<td>1.0</td>
<td>8.2</td>
<td>31.5</td>
<td>732.3</td>
</tr>
<tr>
<td>1.5</td>
<td>8.7</td>
<td>25.3</td>
<td>876.9</td>
</tr>
</tbody>
</table>

*Hall-Petch constant, $k=18$ MPa/mm$^{-0.5}$

Strengthening by oxygen solid solution

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Oxygen Solid Solution Strengthening of P/M Titanium Material

Theoretical analysis; Labusch model applied to Ti-O system

Critical shear stress, \( \tau_0 \) expressed as follows;

\[
\tau_0 = \left( \frac{F_m^4 c^2 W}{4 G b^9} \right)^{1/3} \quad (eq.1)
\]

\[
\Delta \sigma = \frac{\tau_0}{S_F} = \frac{1}{S_F} \left( \frac{F_m^4 c^2 W}{4 G b^9} \right)^{1/3} \quad (eq.2)
\]

- \( S_F \): Schmid factor (=0.44 ~ 0.46)*
- \( c \): Solutinized oxygen content
- \( \tau_0 \): Critical shear stress
- \( F_m \): maximum interaction force
- \( W \): \(~ 5b\)

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High-Strength Pure Titanium Materials Using TiH$_2$+TiO$_2$ Powders

Same effect of TiO$_2$ additives on tensile properties in use of TiH$_2$ as CP-Ti powder

Further strength improvement by “Grain Refinement”?

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High-Strength Pure Titanium Materials Using TiH$_2$+TiO$_2$ Powders

TiH$_2$+1.5%TiO$_2$ mixed powders

Oxygen solid solution & grain refinement cause much superior tensile strength and ductility to Ti-64 alloy

Extruded materials

<table>
<thead>
<tr>
<th>0.2%YS</th>
<th>UTS</th>
<th>Elon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPa</td>
<td>MPa</td>
<td>(%)</td>
</tr>
<tr>
<td>1.5wt.%TiO$_2$-900°C</td>
<td>990</td>
<td>1158</td>
</tr>
<tr>
<td>1.5wt.%TiO$_2$-1000°C</td>
<td>947</td>
<td>1093</td>
</tr>
<tr>
<td>Ti-6Al-4V (TAB6400H)</td>
<td>918</td>
<td>1047</td>
</tr>
</tbody>
</table>

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Oxygen Solid Solved P/M Ti-64 Alloy and Its Application

Matrix; Atomized *Ti-64 alloy powder* 

$\text{TiO}_2$ content; 0, 0.5 and 0.8 wt.%

Sintering temperature; **800°C** for 90min.
Diameter; 60mm, Height; 70mm
Relative density; 92～95%

Extrusion temperature; **1000°C**
Plate width; 42mm, Thickness; 10mm
### Tensile properties of extruded P/M Ti-64 with TiO₂ additives

<table>
<thead>
<tr>
<th>TiO₂ content</th>
<th>L (mm)</th>
<th>0.2%YS (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 wt%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-0°</td>
<td>10</td>
<td>1133.3</td>
<td>1133.4</td>
<td>22.5</td>
</tr>
<tr>
<td>E-0° -1</td>
<td>15</td>
<td>1164.4</td>
<td>1168.1</td>
<td>12.3</td>
</tr>
<tr>
<td>E-0° -2</td>
<td>15</td>
<td>1072.7</td>
<td>1076.8</td>
<td>19.8</td>
</tr>
<tr>
<td>0.5 wt%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-0°</td>
<td>10</td>
<td>1173.7</td>
<td>1226.4</td>
<td>22.7</td>
</tr>
<tr>
<td>E-0° -1</td>
<td>15</td>
<td>1126.5</td>
<td>1199.7</td>
<td>18.6</td>
</tr>
<tr>
<td>E-0° -2</td>
<td>15</td>
<td>1099.7</td>
<td>1186.4</td>
<td>20.2</td>
</tr>
<tr>
<td>0.8 wt%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-0°</td>
<td>10</td>
<td>1280.9</td>
<td>1295.9</td>
<td>14.1</td>
</tr>
<tr>
<td>E-0° -1</td>
<td>15</td>
<td>1227.6</td>
<td>1267.9</td>
<td>10.4</td>
</tr>
<tr>
<td>E-0° -2</td>
<td>15</td>
<td>1233.2</td>
<td>1267.8</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Number of test specimens, N=3

Extrusion direction
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<table>
<thead>
<tr>
<th>θ = 0</th>
<th>0.2%YS MPa</th>
<th>UTS MPa</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO₂; 0%</td>
<td>1123</td>
<td>1126</td>
<td>18.2</td>
</tr>
<tr>
<td>TiO₂; 0.5%</td>
<td>1133</td>
<td>1204</td>
<td>20.5</td>
</tr>
<tr>
<td>TiO₂; 0.8%</td>
<td>1247</td>
<td>1277</td>
<td>12.3</td>
</tr>
<tr>
<td>θ = 90</td>
<td>0.2%YS MPa</td>
<td>UTS MPa</td>
<td>Elongation %</td>
</tr>
<tr>
<td>TiO₂; 0%</td>
<td>1106</td>
<td>1101</td>
<td>21.2</td>
</tr>
<tr>
<td>TiO₂; 0.5%</td>
<td>1075</td>
<td>1148</td>
<td>17.6</td>
</tr>
<tr>
<td>TiO₂; 0.8%</td>
<td>1266</td>
<td>1286</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Projectile illustration

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**Summarized**

**Powder metallurgy process** gives great opportunities to reduce materials cost and improve mechanical performance of titanium and its alloys;

- P/M pure Ti material using TiH$_2$ powders shows high strength and ductility
- Carbon, Nitrogen & Oxygen elements effective for good balance between tensile strength and elongation at ambient temperature
- Oxygen solid solution strengthening effect in P/M Ti-64 alloy is **NOT enough** for improvement of ballistic performance. Uniform dispersion technique of TiO$_2$ in mass should be established.
As Near Future Works ....

Extremely cost-effective process by powder metallurgy;

- **Direct Use of Sponge Ti blocks** as starting materials to fabricate high strength & ductility pure Ti material via solid-state processing

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Thank you for kind attention and Questions?

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