Outline

1. Current Pulse of the Novel Metal Routes
   - ITP, Metalysis, TiRO, Alloys, & Peruke – Maturation is slower than expected

2. Rising Tide Floats all Boats – R&D on Titanium Should benefit the industry broadly
   - Kinetics versus Equilibrium
   - Continuous versus Batch
   - Cost of Capital allows current industry to supplement with new tech
   - Grow the total Ti market with newer applications with less demanding requirements

3. Quality Aspects
   - Challenging to be sure
   - Continuous monitoring
   - Grain structure can be controlled through simple sieving
   - Segregation related defects controlled
   - Cleaner article for inspection (randomly oriented grains of uniform size)
   - Inspectable flaw size
   - Decrease in property variation

4. Conclusions & Summary
Motivation – It’s Difficult to Predict the Future with Certainty?

Bruce Gonser of Battelle Memorial Institute, in the AIME Journal of Metals, January 1, 1949


Investment in R&D is Good for the Industry

Most novel processes share very little with the legacy Kroll process
- TiRO uses Kroll chemistry
- Armstrong use Hunter chemistry

Novel processes are working towards continuous production methods
- Continuous distillation when developed could be incorporated into legacy plants for increased efficiency
  - Newer methods that consume less energy and touch labor could be used for expansion
  - Newer methods are less capital intensive allowing for better ROI during high demand

End uses of a powder product are nascent and limited presently
Applications for Ti powder, even niche, are a growth prospect for the industry simply because new products can be born from PM approaches
Example - TiRO™ Titanium
A continuous titanium production process

The advantages of the TiRO™ process

Efficient – Low use of energy per tonne of titanium produced

Capital – Significant reduction of Kroll capital requirement

Continuous – Low labour, high output continuous production

Key Features:
- Fluidised Bed Reactor
- Continuous Vacuum Distillation
TiRO™ Titanium
A continuous titanium metal production process

Current status of the TiRO™ project

In construction of a 10 tpa plant in Melbourne, VIC at Coogee Titanium

Optimizing TiRO™ flowsheet for ‘sponge’ production

Understanding morphology considerations:
- Native powder tap density ~50% (> 2.2g/cm³)
- Hollow, porous, irregular spheres

<table>
<thead>
<tr>
<th>Element</th>
<th>%wt</th>
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<tbody>
<tr>
<td>Titanium</td>
<td>&gt; 99.7</td>
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<tr>
<td>Oxygen</td>
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<tr>
<td>Nitrogen</td>
<td>&lt; 0.01</td>
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<tr>
<td>Carbon</td>
<td>&lt; 0.01</td>
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<tr>
<td>Iron</td>
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<tr>
<td>Sodium</td>
<td>&lt; 0.02</td>
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<tr>
<td>Chlorine</td>
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<td>Others (Total)</td>
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Capital Cost – Comparison of TiRO™ to Kroll

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<thead>
<tr>
<th>COMPANY</th>
<th>TECHNOLOGY</th>
<th>CAPACITY</th>
<th>COST BASIS</th>
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<tbody>
<tr>
<td>KMML – India</td>
<td>Kroll - Greenfield</td>
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<tr>
<td>RTI – Mississippi</td>
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<td>ATI – Albany</td>
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<td>Toho - Japan</td>
<td>Kroll - Brownfield</td>
<td>3.6k tpa</td>
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Greenfield Comparison:

- TiRO™ ‘Worst Case’ Capital Cost  
  40% of average

TiRO™ capital cost is significantly below Kroll Ti plants

TiRO - Internal Report from Alex Kingsbury, CSIRO Process Science Engineering
Operating Cost – Comparison of Novel to Kroll

Typical Kroll process operating cost

- Feedstock: 15%
- Raw Material: 14%
- Electricity & Services: 28%
- Labour: 14%
- Maintenance: 21%
- Other: 8%

TiRO process operating cost

- Feedstock: 75%
- Raw Material: 53%
- Electricity & Services: 2%
- Labour: 11%
- Maintenance: 9%
- Other: 8%


TiRO - Internal Report from Alex Kingsbury, CSIRO Process Science Engineering
Cost of Material Could Open New Markets

Most of the novel metal production techniques produce a particulate output.

Affordable powder can be a disruptive technology for competing materials (inconels, Cu-Ni alloys and stainless steel).

Particulate can be converted efficiently into Sheet, Rod, Wire, Coatings and Near Net Shapes.

- The disruption is then the ability to reduce mill losses for some finished products.
- There is a cost benefit for thinner, narrower, smaller diameter mill products.
Processing Conversion

Powder is a flexible “mill product”

For thinner sheet and smaller diameter product, a particulate approach is more efficient

Current market is appreciably smaller in these areas but then a supplier can hold a “generic” common input stock of powder and convert it to a range of products on demand leading to less inventory and lower conversion losses

The conversion of particulate to product can be lower cost at the right dimensions
Energy and Environment

A study presented by GE:

Conversion of particulate into bar could represent as much as a 50% reduction in energy consumption for the same end product.

Greener process than current Kroll plus melt-based technology including efficient recycling of by-products. In the same process model referred to above, the lbs of generated CO2 per lb of meltless Ti-64 bar indicate an advantage of 50% less CO2 versus the conventional process.¹

Performance

Studies performed by Lockheed Martin and ORNL have shown that mechanical property variation could well be minimized.

Again, the same benefits we see in other areas around uniformity in grain size play out again, through reduced variation.

While the typical tensile properties are arguably the same as conventionally processed material, statistically derived minimums could be higher.

<table>
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<tr>
<th>Consolidation</th>
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<th>Ftu (MPa)</th>
<th>Fty (MPa)</th>
<th>EI (%)</th>
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<td>945</td>
<td>862</td>
<td>15</td>
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<tr>
<td>PIF</td>
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<td>841</td>
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<tr>
<td>PIF</td>
<td>Super Transus PIF + Beta Anneal</td>
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<tr>
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<td>Super Transus PIF + Rolled + Beta Anneal</td>
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<td>Mill Annual Forging</td>
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<td>862</td>
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</table>

Next Generation

Benefits of alloying additions have always been problematic for commercial reasons.

In addition to the cost to qualify, the downstream impact on the revert is significant (largely due to typically high buy:fly values for complex shapes).

However, if the material utilization is maximized, the acceptance of novel materials and processes is improved.

If new methods are more flexible and can provide smaller quantities affordably, new applications are possible.

An old example is what small additions of Boron due to Titanium strength and modulus:

• Another GE example shows what less than 1% of B in CP Ti can do
• Performance and cost implications are significant

**Novel Alloys**

The ability to formulate new alloys made by PM is potentially quite important.

New reduction technologies that enable alloys that cannot be produced by ingot metallurgy is an exciting longer term possibility.

Will non equilibrium production and processing alter the future of the titanium industry?
Quality

Because the beginning particle size can be selected, the opportunity exists to have a “Cleaner” component to inspect

Traditional issues like segregation and texture will be eliminated, if not minimized

- In this example, GE processed powder via compaction, HIP, extruded bar and forging to an air foil shape
- The resulting component was inspected via traditional C-Scan
- The handling defects (~50μm) were clearly visible in the powder derived part due to the practical absence of background noise
- There is a clear argument that such processing methods could result in smaller, minimum detection criteria

Secondly, continuous production methods have inherent benefits in terms of quality

Continuous monitoring of chemistry, temperatures and processing conditions could improve the industry’s proven quality track record

Directly from Powder to Finish Product

Titanium powder

Cold Spray Titanium
Heat treated & etched
In Summary

Research and Development in Titanium, that expand the uses of Ti and Ti alloys, whether it be new alloys, novel processes or manufacturing technologies are beneficial for the whole industry. Long term, new reduction processes that enable new alloys can be very important in this regard.

New technology can find its way into existing factories
  Continuous production
  Energy Efficient

Particulate metal may open new applications for titanium
  Challenging qualification path as always
  Potential benefits in quality inspection
  Novel methods have a lower capital cost requirement, but still lower if combined with existing facilities
Thank you

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