Direct Powder Rolling (DPR) of Titanium.
Manufacture of titanium products

- Titanium products considered very expensive due to costs of raw materials and manufacturing routes
- Drive to lower both primary and fabrication costs
- Powder metallurgical processing considered to offer significant opportunities
  - Extensive recent effort to develop "lower" cost powder alternatives
  - Strategy to introduce step changes rather than incremental advances
  - NNS manufacturing – reduction in buy-to-fly ratio

[After Froes and German, 2000]
Direct powder rolling of titanium

Consolidation by direct powder rolling of strip is not new – number of processes developed especially in 1950’s-1960’s. Generally involves sintering step to fully densify and homogenise microstructure followed by further hot or cold rolling.

Advantages include:

- Capital equipment savings from a reduction in processing steps.
- Production of higher purity strip, free from segregation and with higher yield.
- Production of fine-grained, high strength strip with no preferred texture.
- Production of sheet from specialty and difficult-to-work materials.
Direct Powder Rolling (DPR) of Titanium Sheet.

**DPR/HRD process schematic**

- **Powder feedstock**
  - Morphology
  - Flow properties
  - Fill/tap density
  - Chemistry

- **Consolidated Strip**
  - Processing
  - Properties
  - Chemistry
  - Microstructure

- **Green Sheet**
  - Density
  - Dimensional accuracy

- **Hot Rolling**
  - Controlled Atmosphere

- **Cold Rolling**
  - Mill Anneal
  - Consolidated Strip

- **Other operations**
  - Ti powder (drums)
  - Powder conditioning
  - Intermediate storage
  - Powder feeder
  - Powder rolling
  - Trimmer
  - Heating
  - Hot rolling
  - Cooling
  - Coiling
  - Trimming/coiling
  - Annealing
  - Cold rolling
  - Storage
Direct powder rolling - DPR

Issues:
- Roll gap
- Roll speed
- Hopper design and positioning (powder flow)
- Edge retention

Green density ~80-85% TD.
Direct powder rolling

- Influence of powder morphology and flow properties on powder rolling
  
  ![Increasing powder rollability](image1)
  ![Increasing powder flowability](image2)

- Rolling loads and compaction behaviour/ ratio also influenced by particle size distribution, fill and tap density, interstitials content (oxygen), and composition (for example CP Ti versus PA Ti6Al4V)
Hot roll densification - HRD
CP Ti

- Evaluation of process window conditions for CP Ti
- Preheat temperature > β transus temperature
- Density increase < 10% on heating only
- Rolling thickness reduction > 40%
- Counter flow inert gas, 200 ppm O₂ max pick-up.
- Sheet density > 99.5% TD
- For CP Ti, UTS ranges from 500-750 MPa and elongation to failure from 14-19% (depending on the oxygen content)
- Mechanical properties and correlation with microstructure, chemistry, texture and residual stresses
## Production of Ti-6Al-4V Strip by DPR/HRD

### Diagram:
- **β phase field**
- **α+β phase field**

### Processing Steps and Parameters:

<table>
<thead>
<tr>
<th>Processing Step</th>
<th>Parameters Tested</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>First hot rolling pass</td>
<td>Temperature, deformation, dwell time &amp; rolling speed kept constant</td>
<td>-</td>
</tr>
<tr>
<td>Second hot rolling pass</td>
<td>Temperature, Degree of deformation</td>
<td>Above &amp; below β transus&lt;br&gt;Two levels: &lt;60% &amp; &gt;60%</td>
</tr>
<tr>
<td>Anneal 1</td>
<td>Temperature, Hold time at temperature, Cooling rate, Atmosphere</td>
<td>Above &amp; below β transus&lt;br&gt;20 mins &amp; 60 mins&lt;br&gt;Air cool &amp; furnace cool&lt;br&gt;Vacuum &amp; argon</td>
</tr>
<tr>
<td>Anneal 2</td>
<td>Temperature, Hold time at temperature, Cooling rate</td>
<td>540°C &amp; 750°C&lt;br&gt;1 hr &amp; 4 hrs&lt;br&gt;Air cool and furnace cool</td>
</tr>
</tbody>
</table>
Results – Microstructure and Properties

Density is 99.6%, the oxygen pick-up during the process cycle was low
Coarse $\alpha + \beta$ lamellae, typical of furnace cooled microstructures

<table>
<thead>
<tr>
<th>UTS (MPa)</th>
<th>0.2% Proof Stress (MPa)</th>
<th>Elongation to Failure (%)</th>
<th>Density (%)</th>
<th>Interstitial Content (wt. %)</th>
<th>Microstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1061</td>
<td>970</td>
<td>8.8</td>
<td>99.6</td>
<td>0.23% O, 0.02% N, 0.018% H</td>
<td>homogeneous</td>
</tr>
<tr>
<td>991</td>
<td>915</td>
<td>6.8</td>
<td>99.4</td>
<td>-</td>
<td>inhomogeneous</td>
</tr>
</tbody>
</table>

On going optimisation trials

Direct Powder Rolling (DPR) of Titanium Sheet.
Conclusions

- A process for the direct rolling of Titanium sheet from powder has been discussed.
- Powder morphology, flow and packing density as well as the roll mill physical characteristics all impact powder compaction on rolling.
- The combination of roll compaction and in-line rapid heating prior to hot roll densification (HRD) has the potential to reduce manufacturing costs.
- Control of heating, atmosphere and hot rolling conditions are also essential if the required microstructure is to be achieved.
- Work on titanium alloys such as Ti6Al4V also very encouraging with further work scheduled for other alloy systems.
- The DPR facility can also be applied to other metal and composite systems including functionally graded and layers structures.
- CSIRO is actively seeking Industry participation in further development and commercialisation of the technology.
Thank you

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