Melting and Casting of Titanium Aluminides

Challenges and Opportunities

Henrik Franz
ALD Vacuum Technologies GmbH, Hanau, Germany
**Titanium Aluminides**

1st Generation  
*Ti x Al (1970-1980)*

2nd Generation  
*Ti-48Al-2Nb-2Cr (1990)*

3rd Generation  
*Ti-45Al-8Nb-0.2C-0.2B (2000)*

4th Generation  
*Ti-46Al-8Ta (2009)*

- $\alpha_2$-Ti$_3$Al (hexagonal) + $\gamma$-TiAl ($L_1_0$-cubic face centered)
- Intermetallic comp. → high temp. strength
- lightweight (3.8-4.5 g/cm$^3$)
- oxidation resistance (700-800 °C)
- low RT ductility (< 1%)

Al-content & alloying elements → micro structure
→ creep strength, oxidation resistance, $\alpha$ & $\beta$- transition temp.

- Impurities (e.g. Oxygen) → RT ductility $\downarrow$
- Processing: casting, hot extrusion, forging, powder metallurgy
- Heat treatment processes → microstructure adjustment

**UTILIZATION of TiAl – POTENTIALS -> TIGHT ALLOY SPECIFICATION & LOW IMPURITY CONTENT**
**Titanium Aluminides – Alloy Production**

- Reliable alloy production
- Feedstock selection, preparation and flexibility
- Homogenization
- Suppression and compensation of loss of volatile elements

**2 MAIN PRODUCTION ROUTES**

- **PLASMA**
- **VAR**

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![Graph showing binary titanium aluminum alloy](image)

![Graph showing evaporation rate](image)

- Minimization of local superheating (Heat of Mixing)
- Excellent leak tightness
- Cold wall techniques
- Process monitoring
Titanium Aluminides - Alloy Production – Plasma Melting (PAM)

- Continuous Production Method (*Feeding & Withdrawal*)
- Melting under Helium or Argon (*up to 1 atm.*)
- Minimization of evaporation loss
- Flexible feedstock handling

- Excellent homogeneity
- Scrap recycling up to 100%

- Ingot diameter  $\rightarrow$ productivity
  $\rightarrow$ risk of brittleness

- Processing under inert gas  $\rightarrow$ online control of process gas
  $\rightarrow$ gas recycling

- Limited refining capabilities
Titanium Aluminides - Alloy Production – Vacuum Arc Remelting (VAR)

- Batch Production Method (1 Electrode = 1 Ingot)
- Melting under vacuum
- Compensation of evaporation loss by additional material
- Limited feedstock flexibility

- Electrode preparation by pressing & welding
- 2-3 times re-melting for proper homogenization
- Lowest oxygen, nitrogen and hydrogen contents
**Titanium Aluminides – General Requirements for Casting Processes**

Critical flow characteristic of TiAl-alloys
- Reduction of temperature loss while pouring
- Superheat is important
- Casting in hot mold
- Stable ceramic shell system
- Turbulence minimization
- Avoidance of inert gas entrapment

Special Mold Design
- Heating and cooling of the mold
- Heat expansion of TiAl-alloys
- Ductile → Brittle transition during cooling

Precise temperature management required
- TiAl-alloys tend to crack during cooling
**Titanium Aluminides – Melting Techniques – VAR Skull Melt**

**Process Characteristics**
- Low cycle time → high productivity
- Easy to operate and to maintain
- Easy process control
- High reliability/repeatability
- Electrode for multiple pours
- Low production costs
- Up to 1t pouring weight
- Limited scrap recycling
- Turbulent mould filling
- Small batch weights difficult
**Titanium Aluminides – Melting Techniques – Cold Wall Induction Crucible (CIC)**

**Process Characteristics**
- Excellent homogenization (thermal & chemical)
- Recharging and alloying
- 100% Scrap recycling
- No risk of impurity pick up
- Unlimited holding time
- Multi-chamber design possible
  - Vacuum or inert gas
  - High energy consumption
  - High cooling water demand
  - 0.5 – 140 kg pouring weight
  - Limited superheat
  - Turbulent pouring process
Oxygen solubility in binary Titanium Aluminum alloys depend on:

- **Al-Content**
- **Temperature**

- γ-TiAl: Al-content < 50 at.%
  → oxygen equilibrium content > 1%

⇒ If oxygen source available no fail system to limit oxygen pick up exists
**Titanium Aluminides – Melting Techniques – Ceramic Crucible**

- Yttrium contents around 0.5 wt.%
  - Oxygen < 1000 ppm wt.
- Strong temperature dependence
- Risk of formation of Yttria-inclusions during solidification
  - Impact on properties
- Calcium contents around 0.2 wt.%
  - Oxygen < 1000 ppm wt.
- Calcium evaporates from melt
  - Oxygen enrichment
- CaO-Crucibles difficult to handle (hygroscopic)
- Both ceramic systems provide temporary protection only
  - depending on Temperature
  - Contact time
- Oxygen pick up will occur
  - Feedstock has to be low in oxygen
Titanium Aluminides – History ALD

- TiAl-Powder Production by EIGA/VIGA
- EU-Project “IMPRESS”
- 1995
  - TiAl-Valve Production Proto-Type “Wheelcaster”
- 2000
  - TiAl-Valve Casting CIC + Permanent Mould
- 2014
  - Investment Casting TiAl-Turbocharger Wheels & Turbine Blades
**Titanium Aluminides – Processing Routes – Automotive Valve Casting**

- Continuous production process
- Cold Wall Induction Crucible + Centrifugal Casting
- Low cost approach
- Vertical mould spinning
- 50 Valves / cycle
- Excellent mould filling

- Permanent mould (niobium alloy)
- Cycle time < 25 min
- Up time > 80 % → 500,000 valves/year
Titanium Aluminides – Processing Routes – Automotive Valve Casting

- Excellent mechanical properties (as cast & HIP)
- Chemical uniformity down to micro scale
- Oxygen content below 500-700 ppm wt.
- Plastic elongation >0.5%
- Successful tested

Ready from production
Ready for application
Cost target missed
Titanium Aluminides – Processing Routes – Turbocharger Wheel Casting

- Cold Wall Induction Crucible + Gravity Casting
- Investment casting process
- Significant impact of mould preheating on casting yield
- Shell system to withstand high preheating temperatures
- Casting yield strongly depends on position of mould
- Yield reduction by small part/feeding system ratio

Mould Temperature:
- < 700 °C: Low investment costs, Low yield
- > 800 °C: Misruns
Titanium Aluminides – Processing Routes – Tilt Casting

- Adopted for TiAl by IRC Birmingham for large turbine blades (IMPRESS Project)
- Cold Wall Induction Crucible
- Investment casting process
- Designed pouring sequence (incl. dwell & acceleration phases)
- Mould preheating
- 40 cm IGT-Blades successfully casted
- Long contact time mould/melt
  → stable shell system required
- Process adoptable at industrial scale
- Single piece casting process
  → limited productivity
Titanium Aluminides – Processing Routes

CIC + Counter Gravity Casting
Ceramic Crucible + Centrifugal Casting

- Acceleration starts from zero ⇒ turbulences↓
- Ceramic crucible ⇒ short melting time necessary
  ⇒ small batch weights
- Up scaling by additional casting units only
  ⇒ need for automation
- No mould preheating
- Low oxygen feedstock

- Hitchiner Process adopted by DAIDO (Levicast)
- Melting under vacuum → backfill with argon
- Mould immersion → mould evacuation → mould filling
- Smooth filling
## Titanium Aluminides – Processing Routes – CIC + Ceramic Crucible

<table>
<thead>
<tr>
<th></th>
<th>Ceramic Crucible</th>
<th>Cold Wall Induction Crucible</th>
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</thead>
<tbody>
<tr>
<td><strong>Superheat</strong></td>
<td>Limited by ceramic system</td>
<td>Limited</td>
</tr>
<tr>
<td><strong>Feedstock</strong></td>
<td>Customized</td>
<td>Flexible</td>
</tr>
<tr>
<td><strong>Impurity pick up</strong></td>
<td>• Ceramic system</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>• Superheat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Holding time</td>
<td></td>
</tr>
<tr>
<td><strong>Batch Weight</strong></td>
<td>&lt; 10 kg</td>
<td>2 - &gt;100 kg</td>
</tr>
<tr>
<td><strong>Holding Time</strong></td>
<td>Minimal</td>
<td>Unlimited</td>
</tr>
<tr>
<td><strong>Pouring Process</strong></td>
<td>Adjustable (laminar to turbulent)</td>
<td>Turbulent</td>
</tr>
<tr>
<td><strong>Alloying</strong></td>
<td>No</td>
<td>Limited</td>
</tr>
<tr>
<td><strong>Atmosphere</strong></td>
<td>Protective gas necessary</td>
<td>Vacuum or protective gas possible</td>
</tr>
<tr>
<td><strong>Σ</strong></td>
<td>Preferable for Pouring</td>
<td>Preferable for Melting</td>
</tr>
</tbody>
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Combination of both techniques can offer significant yield improvement at large batch weights.
Titanium Aluminides – Melting and Casting Techniques - Summary

- State of the art TiAl-alloy production by Plasma or VAR
- Customized feedstock for casting processes (suitable size and chemical composition)
- Melt superheat and turbulences during pouring \(\Rightarrow\) Casting yield
- Various casting methods available \(\Rightarrow\) No general judgment
- Casting yield dominates CoO (high material costs)
- HIP and heat treatment of cast parts necessary
Titanium Aluminides – Melting and Casting Techniques - Summary

- **Investment casting/Shell system**
  - Gating and feeding system most important (design by simulations)
  - Stress impact on cast parts during solidification and cooling
  - Sufficient chemical resistance during mould filling

- **Mould preheating favorable**

- **Melting in ceramic crucibles** → Short cycle time → Small batch weights

- **Combination CIC and ceramic crucible** → Batch size ↑ → Casting yield ↑ → Costs ↓

- **Recycling technology necessary**
Thank You

for

Your Patience