Additive Manufacturing of Gamma Titanium Aluminide Parts by Electron Beam Melting (EBM®)

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Outline

• Introduction to Electron Beam Melting
  • Arcam AB
  • EBM process
  • EBM materials
  • EBM applications
• New EBM process for $\gamma$-TiAl
  • Powder properties
  • Heat treatment and microstructure
  • Chemical composition
  • Tensile properties
  • Fatigue properties
• Summary and conclusion
What is Arcam?

- Develops technology for additive manufacturing with EBM
- Swedish innovation, early 1990’s
- Arcam AB founded 1997
- Located in Gothenburg, Sweden
- First EBM machine delivered in 2003
- More than 60 systems installed worldwide
- Main focus (so far): Medical implants and aerospace parts made from titanium alloys
- Some well-known EBM users: Boeing, NASA, Airbus
The EBM process

- Typical powder size: 45-105 μm (-140/+325 mesh)
- Layer thickness: 0.05-0.2 mm
- 3kW electron beam
- Elevated build temperature, e.g. Ti-6Al-4V, ~700°C γ-TiAl, >1000°C
- High vacuum: 10^{-5} mbar
- Build rate: 3-20 mm height/hour
- Build envelope: up to 350×200×200 mm (14×8×8 in.)
EBM metal powders

- Pre-alloyed
- Supplied by selected powder manufacturers
- No binders or additives
- Size fraction selected for safety and production economy
- Provided with optimized EBM machine parameters
EBM materials

• "Commercial" processes developed for:
  • Ti-6Al-4V (Grade 5)
  • Ti-6Al-4V-ELI (Grade 23)
  • Titanium CP (Grade 2)
  • CoCr alloy F75
  • Gamma-TiAl, Ti-48Al-2Cr-2Nb

• Full compliance with ISO and ASTM standards

• Any metal with a melting point up to tungsten (3400°C) can be melted with a 3kW e-beam.
Other materials with proven EBM potential

- Ni-based superalloys (e.g. Alloy 625 & 718)
- Stainless steel (e.g. 17-4)
- Tool steel (e.g. H13)
- Aluminium (e.g. 6061)
- Hard metals (e.g. Ni-WC)
- Copper
- Beryllium
- Amorphous metals
- Niobium
- Invar
EBM applications

- Medical Implants
- Aerospace
- Automotive
- Other
CE-certified implant production since 2007

- Acetabular cups with engineered trabecular structures
- Ti-6Al-4V ELI, 12 cups in 13 hours, stackable 82 cups in 80 h
- > 35000 cups manufactured
- Approx. 7000 cups implanted
Turbine blades in $\gamma$-TiAl

- TiAl collaboration project with Avio SpA in Italy
- Demo turbine blades for the LP stage in GEnx engine
- 325 mm build height
- Dimensional tolerance ±0.1 mm
- Net build time 7 h / blade
- Turnaround time 10 h / blade
Development of an EBM process for $\gamma$-TiAl (Ti-48Al-2Cr-2Nb)

Incentive

- $\gamma$-TiAl is an attractive material for structural aerospace applications at high T:
  - Good oxidation and corrosion resistance
  - Specific strength comparable to Ni-base superalloys
  - Density about 50% of Ni-base superalloys
  - Ti-48Al-2Cr-2Nb is the most well-characterized $\gamma$-TiAl alloy

- Advantages of the EBM process:
  - low level of internal defects, therefore low scatter in material properties
  - homogeneous microstructure
  - very fine grain size, leading to good fatigue properties, and no need for grain refinement
  - no residual stresses due to high process temperature
  - little waste material thanks to vacuum environment: powder can be recycled
Reference data for Ti-48Al-2Cr-2Nb

M.J. Weimer, T.J. Kelly, GE Aviation:
TiAl Alloy 48Al-2Nb-2Cr: Material Database and Application Status

Cast Ti-48Al-2Cr-2Nb, HIP + HT, duplex microstructure

Presented at the 3rd International Workshop on γ-TiAl Technologies, Bamberg, Germany, May 29-31, 2006
EBM $\gamma$-TiAl Powder Properties

- Vacuum induction melted, Ar gas atomized
- Size 45-150 $\mu$m (-100/+325 mesh)

- Spherical pores < 150 $\mu$m
- Originate from Ar bubbles entrapped in the powder
- Closed by HIP
EBM $\gamma$-TiAl Chemical Composition

<table>
<thead>
<tr>
<th>Chemical composition in wt%</th>
<th>Al</th>
<th>Cr</th>
<th>Nb</th>
<th>Fe</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>H</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-48Al-2Cr-2Nb</td>
<td>32.0 - 33.5</td>
<td>2.2 - 2.6</td>
<td>4.5 - 5.1</td>
<td>Max. 0.05</td>
<td>Max. 0.025</td>
<td>Max. 0.12</td>
<td>Max. 0.02</td>
<td>Max. 0.003</td>
<td>Bal.</td>
</tr>
<tr>
<td>Alloy specification</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Powder X</td>
<td>34.1</td>
<td>2.4</td>
<td>4.8</td>
<td>0.03</td>
<td>0.005</td>
<td>0.06</td>
<td>0.004</td>
<td>0.001</td>
<td>Bal.</td>
</tr>
<tr>
<td>Material built with Powder X</td>
<td>33.4</td>
<td>2.2</td>
<td>5.1</td>
<td>0.03</td>
<td>0.008</td>
<td>0.06</td>
<td>0.01</td>
<td>0.0001</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

- Approx. 1 wt% Al loss due to evaporation
- Modified powder chemistry, +1 wt% Al
- Very low pickup of O and N thanks to vacuum environment
EBM $\gamma$-TiAl Microstructures

As-built by EBM

HIP 1260°C, 1700 bar, 4h
Equiaxed $\gamma$
Grain size $<20 \mu$m

Heat Treatment
Duplex
Lamellar colonies $\sim 100 \mu$m
Equiaxed grains $\sim 15 \mu$m
Lamellar fraction $\sim 40\%$
EBM $\gamma$-TiAl Tensile Properties

- UTS/YTS virtually independent of temperature up to $\sim 815^\circ$C
- Brittle-Ductile Transition Temperature (BDTT) between 700 - 800°C
- Similar behavior as cast material
- Ref. UTS=450 MPa (65 ksi) in GE database
10% scattering of UTS and 6% of YTS at room temperature, based on >10 tensile specimens per data point

Low scattering compared to cast γ-TiAl and also compared to cast Ni-superalloys
Aged in air at 650 °C for 10 h
Loss of ductility at lower temperatures compared to non-oxidized
Machining of the surface restores ductility → surface effect!
Similar loss of ductility has been reported for oxidized cast TiAl
EBM $\gamma$-TiAl Fatigue Crack Growth Threshold

Constant amplitude crack growth with load increase

RT, 40 Hz, R=0.05

$6.13 < K_{th} < 6.70 \text{ MPa}\cdot\text{m}^{\frac{1}{2}}$

GE reference: $K_{th} = 4.7 \text{ MPa}\cdot\text{m}^{\frac{1}{2}}$
EBM $\gamma$-TiAl HCF Properties, RT

### Axial Fatigue Test
- Test freq.: 100 Hz
- Testing temp.: RT
- Loading ratio: $R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = 0.6$

- **Failure**
- **Runout**
EBM $\gamma$-TiAl Fatigue Properties, 704°C (1300 F)

- Ref. fatigue limit = 324 MPa in GE database
EBM $\gamma$-TiAl Fatigue Properties, Haigh Diagram

- All HCF data exceed GE reference data!
EBM $\gamma$-TiAl Fatigue Properties, turbine blades

HCF test with turbine blade geometries at RT

- Pre-oxidized 20 hrs at 650°C
- Machined by ECM to surface roughness $R_a=1.6 \, \mu m$
- Average fatigue limit: 400 MPa (58 ksi)

700 Hz

crack initiation
Summary and Conclusions

Core benefits of EBM additive manufacturing:
• Freedom in design
• Very low material waste
• Material properties compliant with standards
• Integrated lattice/cellular structures
• Proven productivity – in continuous serial production since 2007
• Large potential for new materials

Gamma Titanium Alumininide manufactured with EBM:
• 3D geometries (turbine blades) fabricated with proven process stability
• HIP eliminates residual porosity
• Complies with chemical spec. after 1% Al addition to powder
• Fine grain duplex microstructure after proper heat treatment
• Tensile properties equal to GE reference data
• HCF properties exceed GE reference data
• EBM serial production of $\gamma$-TiAl to be launched at AvioProp in Italy
Thank you!

Ulf Ackelid
Arcam AB
γ-TiAl with EBM
Creep properties

Density corrected creep properties compared with Ni-base superalloys for use in LPT’s last stages.
γ-TiAl with EBM
A²X Heat load optimization

- The standard Arcam A2 system is designed for production in Ti6Al4V and CoCr.
- γ-TiAl requires substantially more heat than titanium to be processed in the EBM.
- Higher temperatures to dissolve surface oxides
- The majority of heat is lost through radiation from build area into subsystems.
- Heat load optimization needed to improve the insulation to ensure correct operating temperatures of subsystems.
$\gamma$-TiAl with EBM

$A^{2X}$ Heat load optimization

Build temperature

$\degree$C

$\gamma$–TiAl Range

$A^{2X}$ operating mode

Titanium range

Arcam A2 normal operating mode
γ-TiAl with EBM

A²X Heat load optimization

The heat load on critical components has been reduced to a minimum by optimizing insulation and at the same time increasing the utilization of available beam power.

- Resulting in a customized A² for serial production of TiAl turbine blades

- Build envelope:
  - 200 x 200 x 375 mm

- With four systems delivered to Avio, May 2010