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

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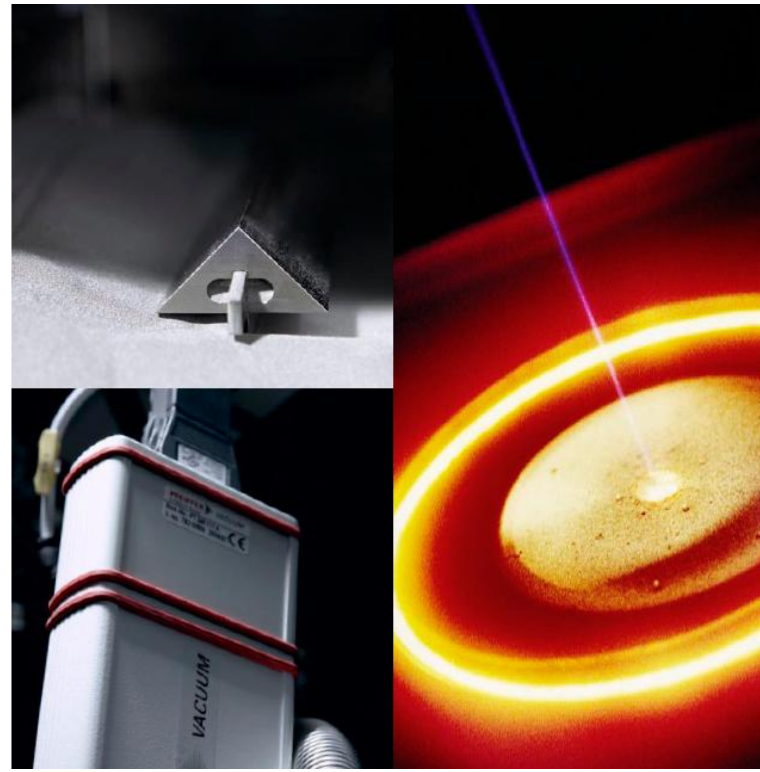
Outline

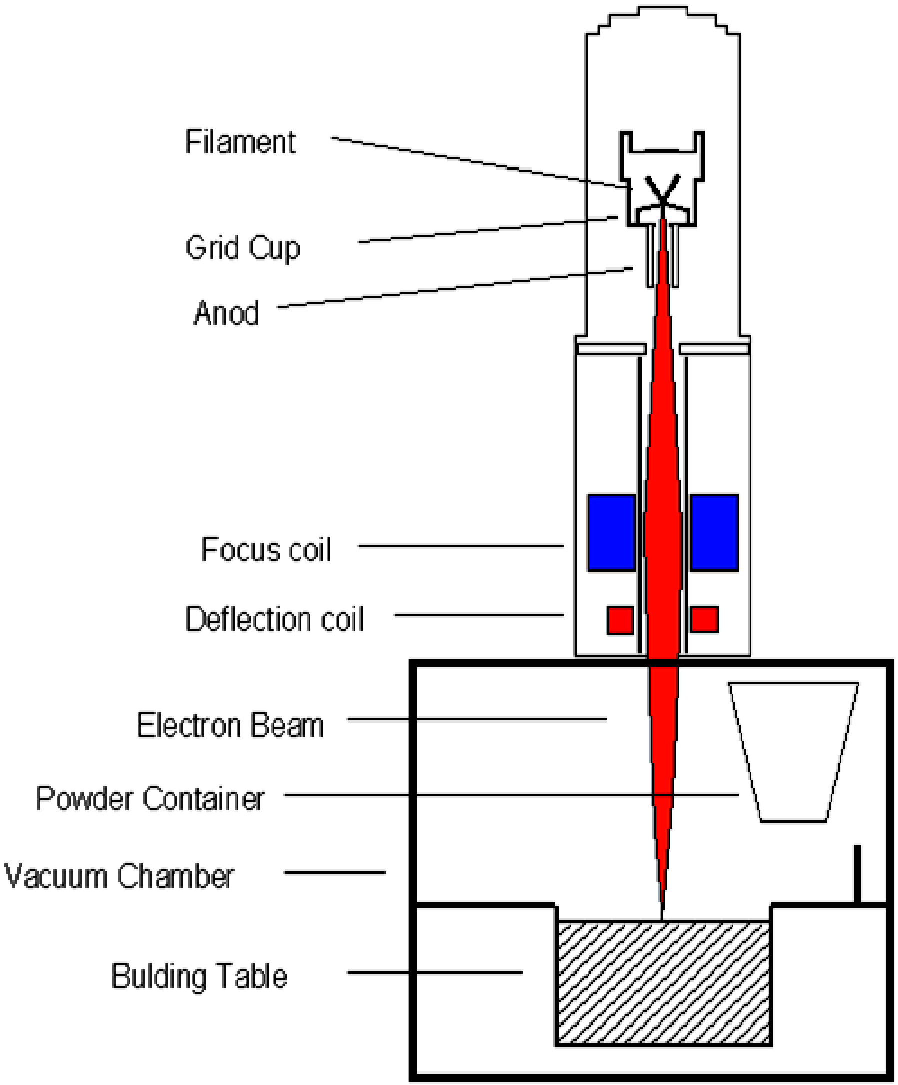
- Introduction to Electron Beam Melting
  - Arcam AB
  - EBM process
  - EBM materials
  - EBM applications
- New EBM process for γ-TiAl
  - Powder properties
  - Heat treatment and microstructure
  - Chemical composition
  - Tensile properties
  - Fatigue properties
- Summary and conclusion



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

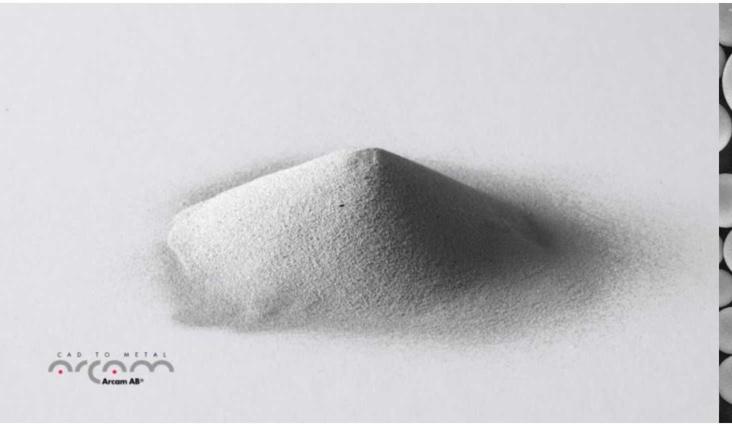
The EBM process

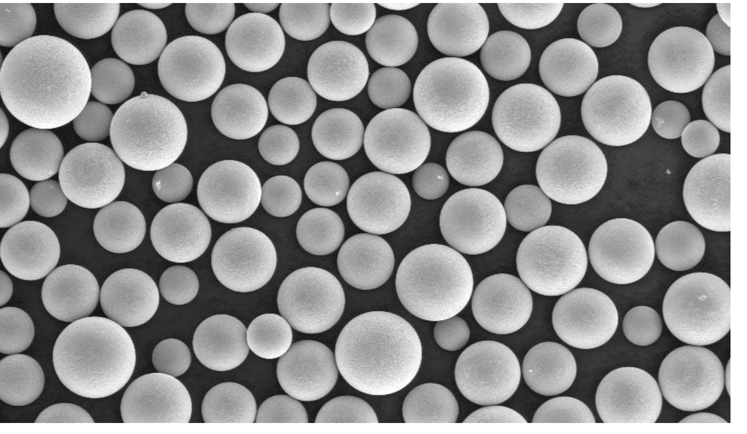


- Typical powder size:
  45-105 µm (-140/+325 mesh)
- Layer thickness:
  0.05-0.2 mm
- 3kW electron beam
- Elevated build temperature,
  e.g. Ti-6Al-4V, ~700°C
  γ-TiAl, >1000°C
- High vacuum:
  10^{-5} mbar
- Build rate:
  3-20 mm height/hour
- Build envelope:
  up to 350×200×200 mm (14×8×8 in.)

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

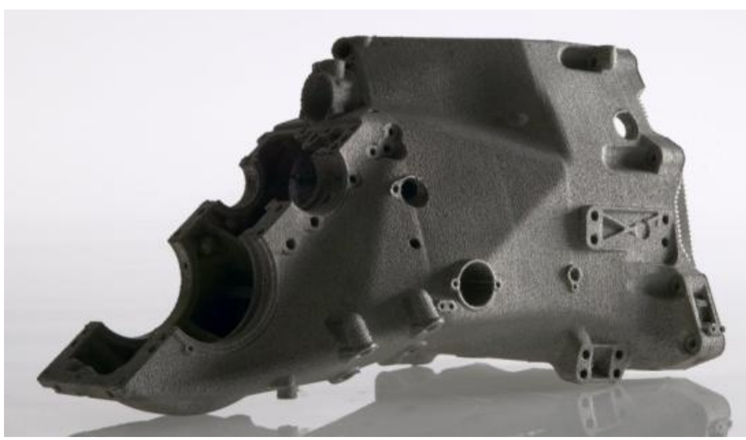
- Any metal with a melting point up to tungsten (3400°C) can be melted with a 3kW e-beam.

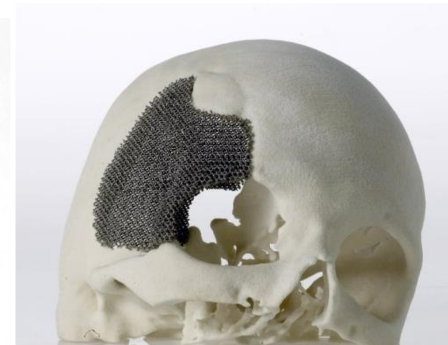
Other materials with proven EBM potential

- 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

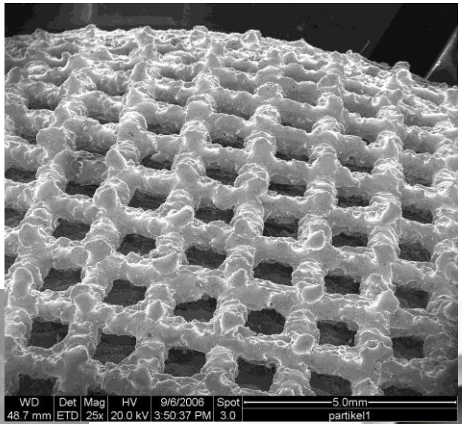
- Medical Implants
- Aerospace
- Automotive
- Other





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 γ-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 γ-TiAl (Ti-48Al-2Cr-2Nb)

Incentive

- γ-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 γ-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

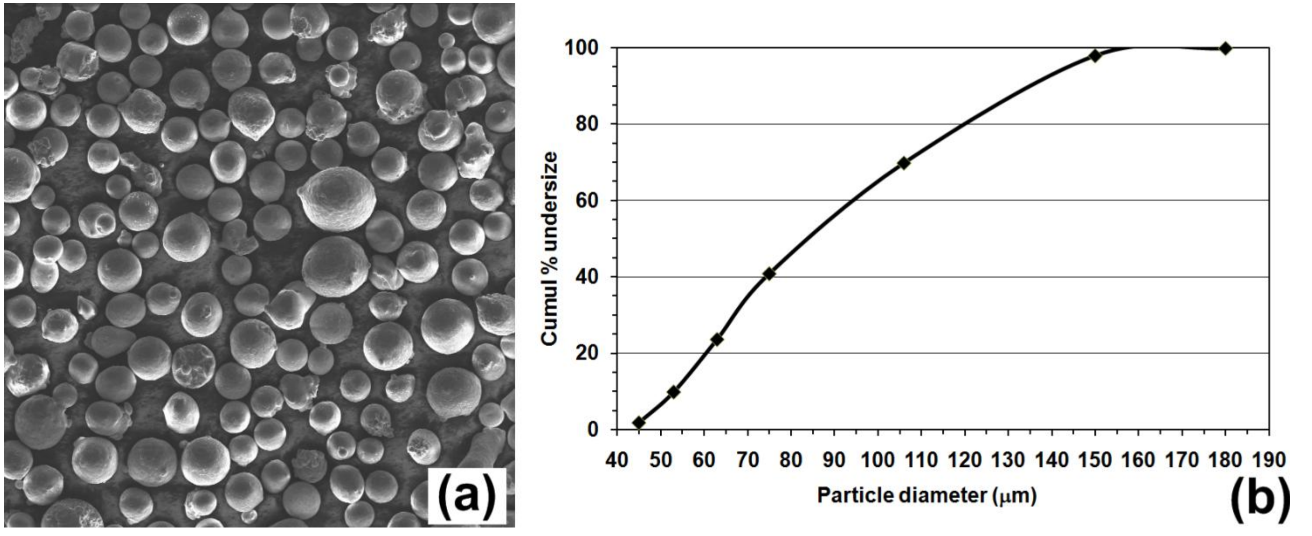
Reference data for Ti-48Al-2Cr-2Nb

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

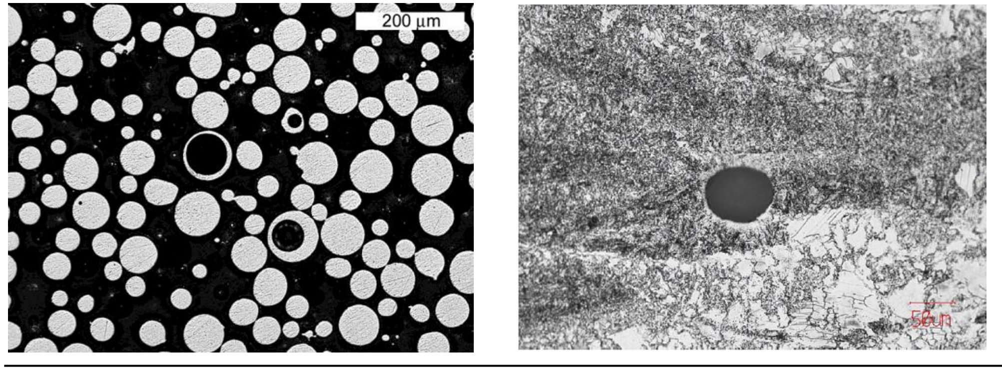
Cast Ti-48Al-2Cr-2Nb, HIP + HT, duplex microstructure

Presented at the 3rd International Workshop on γ-TiAl Technologies, Bamberg, Germany, May 29-31, 2006

EBM γ-TiAl Powder Properties



- Vacuum induction melted, Ar gas atomized
- Size 45-150 μm (-100/+325 mesh)



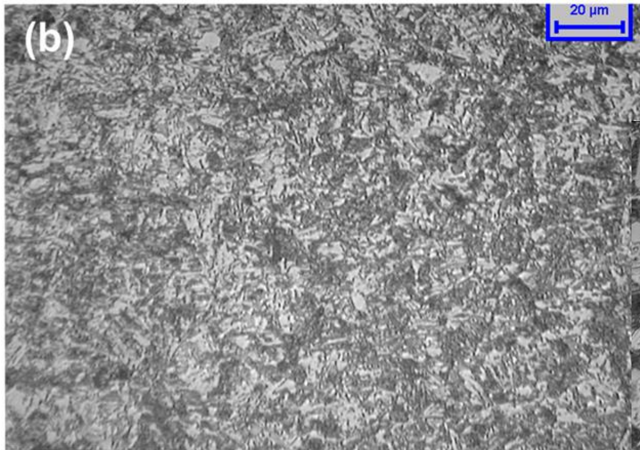
- Spherical pores < 150 μm
- Originate from Ar bubbles entrapped in the powder
- Closed by HIP

EBM γ-TiAl Chemical Composition

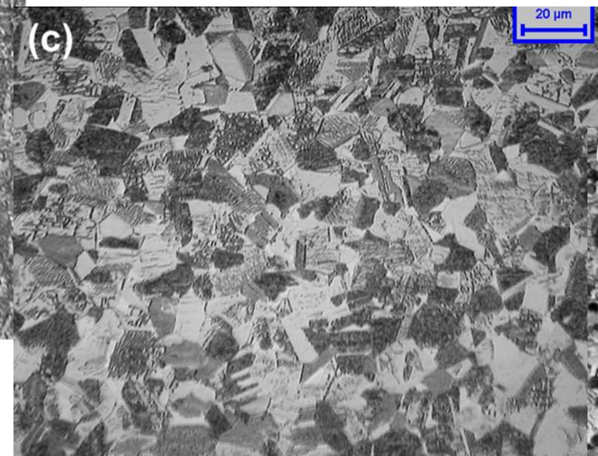
Chemical composition in wt%									
	Al	Cr	Nb	Fe	C	O	N	H	Ti
Ti-48Al-2Cr-2Nb Alloy specification	32.0 - 33.5	2.2 - 2.6	4.5 - 5.1	Max. 0.05	Max. 0.025	Max. 0.12	Max. 0.02	Max. 0.003	Bal.
Powder X	34.1	2.4	4.8	0.03	0.005	0.06	0.004	0.001	Bal.
Material built with Powder X	33.4	2.2	5.1	0.03	0.008	0.06	0.01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

- 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

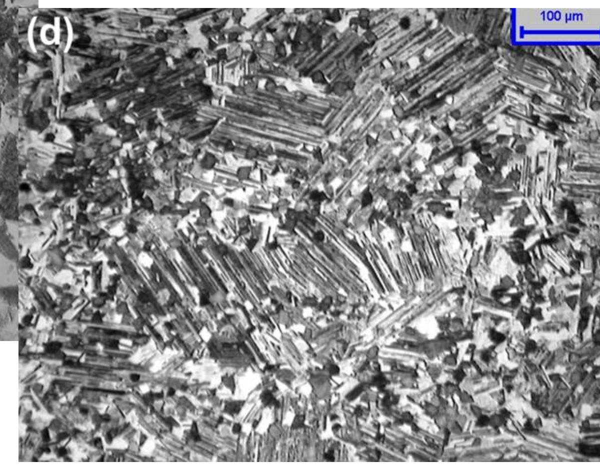
EBM γ-TiAl Microstructures



As-built by EBM

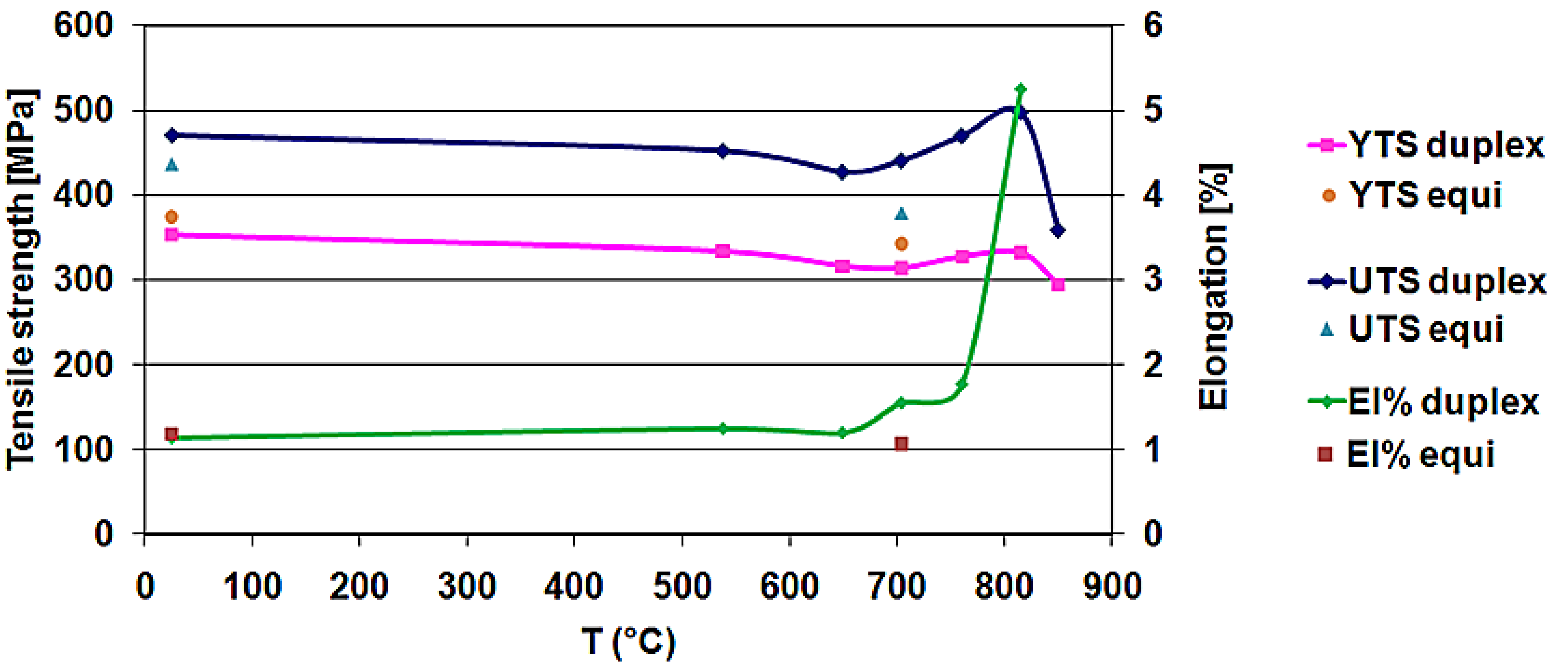


HIP 1260°C, 1700 bar, 4h
Equiaxed **γ**
Grain size <20µm



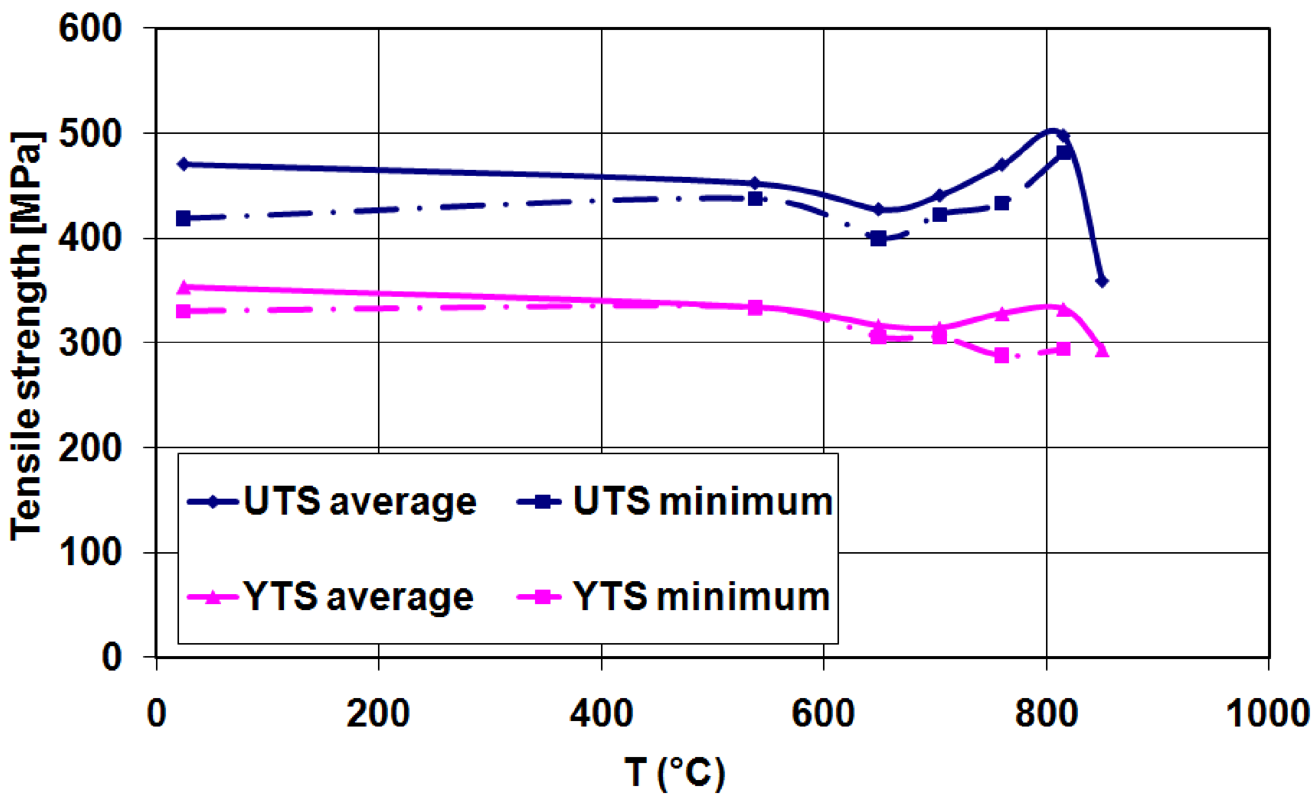
Heat Treatment
Duplex
Lamellar colonies ~100 µm
Equiaxed grains ~15 µm
Lamellar fraction ~ 40%

EBM γ-TiAl Tensile Properties



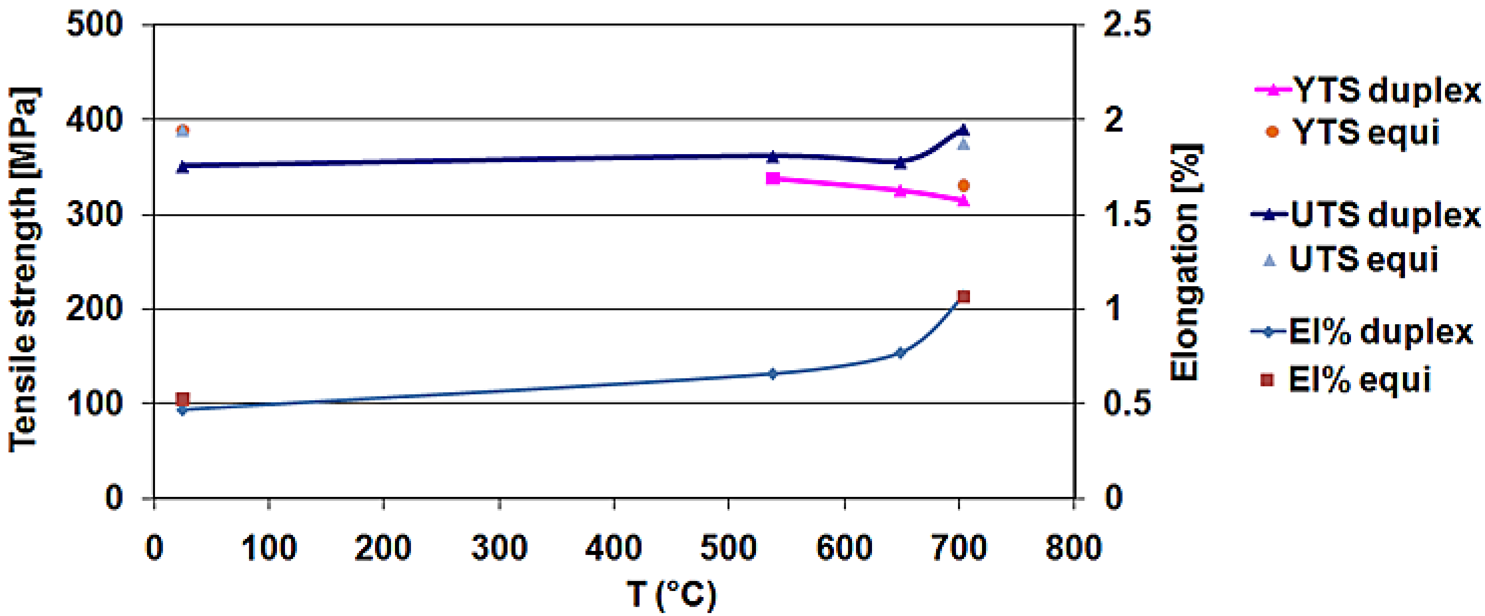
- UTS/YTS virtually independent of temperature up to ~815°C
- Brittle-Ductile Transition Temperature (BDTT) between 700 - 800°C
- Similar behavior as cast material
- Ref. UTS=450 MPa (65 ksi) in GE database

EBM γ-TiAl Tensile Properties, scattering



- 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

EBM γ-TiAl Tensile Properties, after ageing



- 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

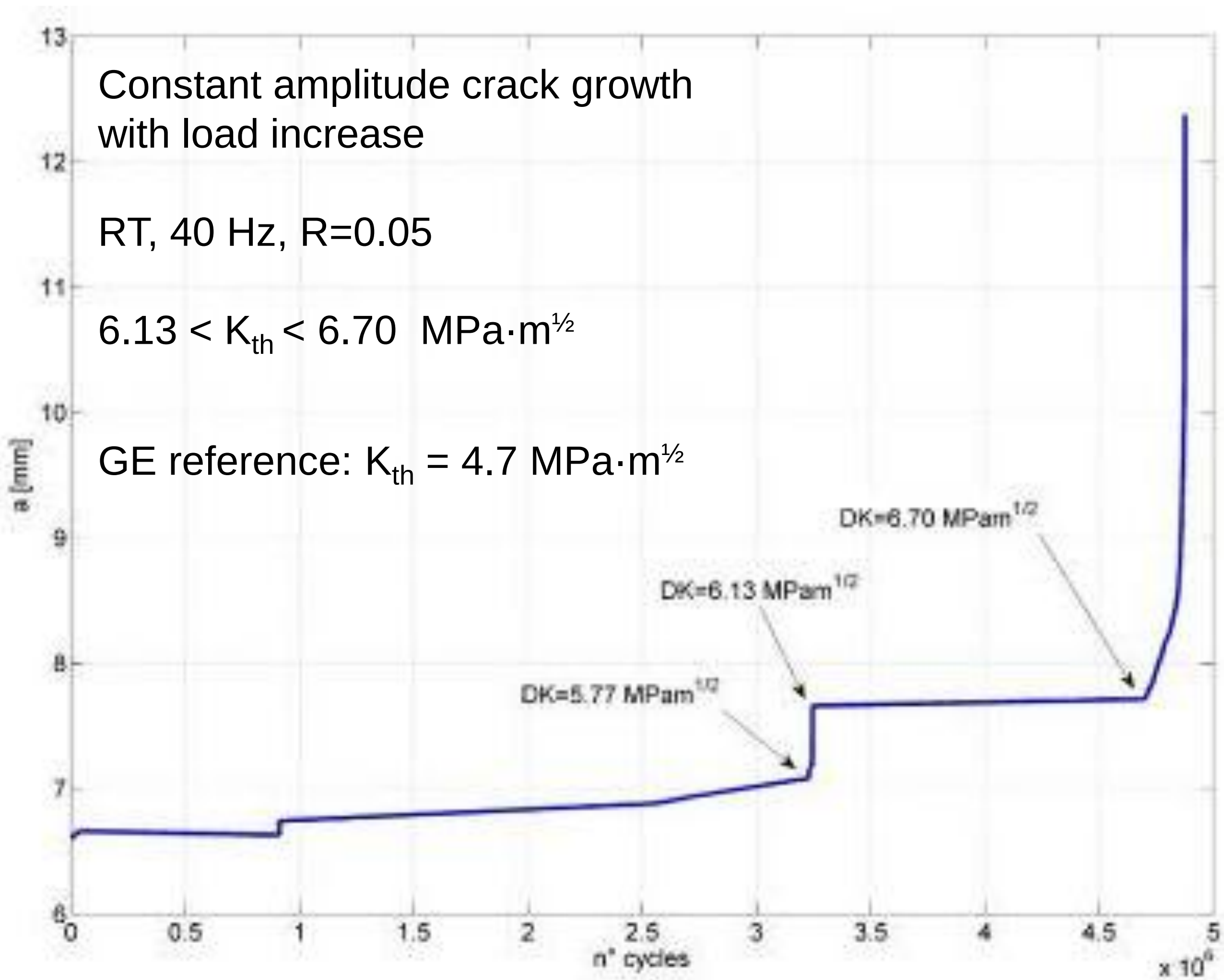
EBM γ-TiAl Fatigue Crack Growth Threshold

Constant amplitude crack growth with load increase

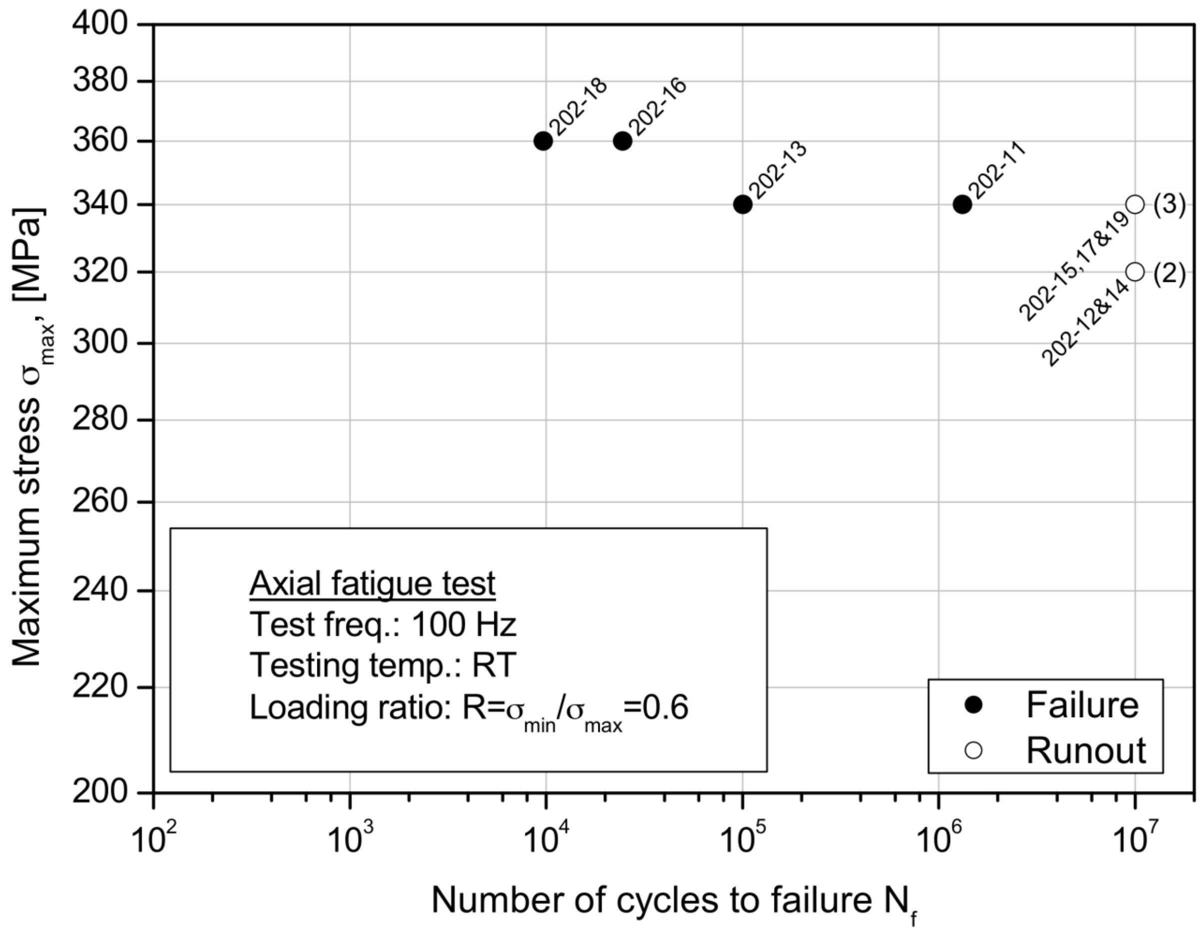
RT, 40 Hz, R=0.05

$6.13 < K_{th} < 6.70$ MPa·m$^{1/2}$

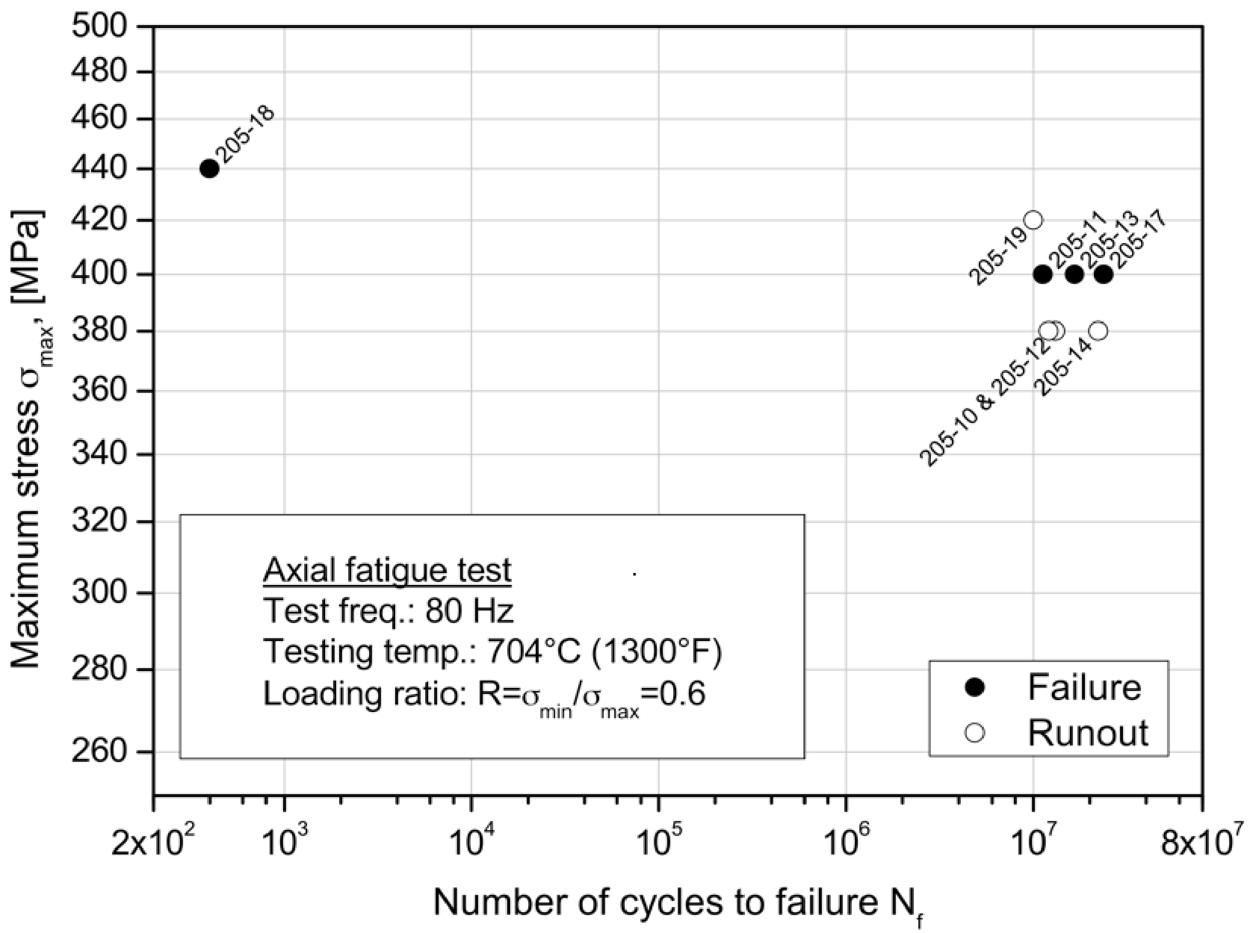
GE reference: $K_{th} = 4.7$ MPa·m$^{1/2}$



EBM γ-TiAl HCF Properties, RT

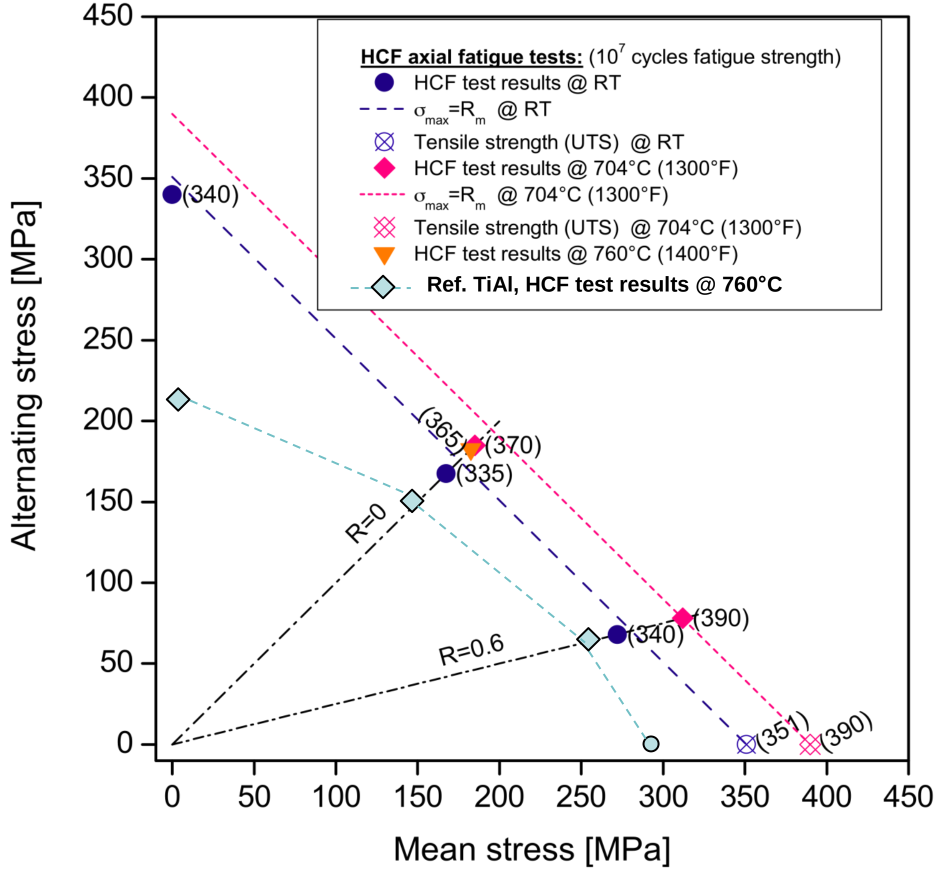


EBM γ-TiAl Fatigue Properties, 704°C (1300 F)



- Ref. fatigue limit = 324 MPa in GE database

EBM γ-TiAl Fatigue Properties, Haigh Diagram



- All HCF data exceed GE reference data !

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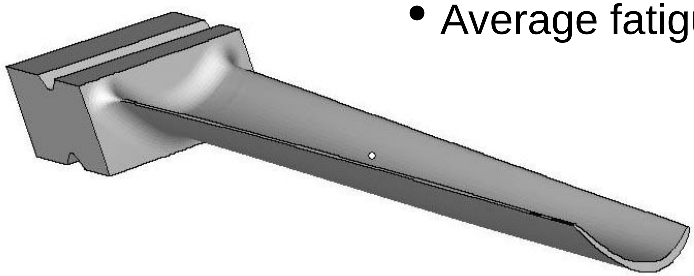
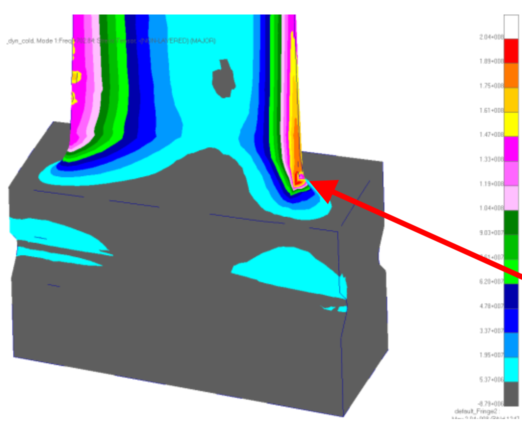
EBM γ-TiAl Fatigue Properties, turbine blades

HCF test with turbine blade geometries at RT

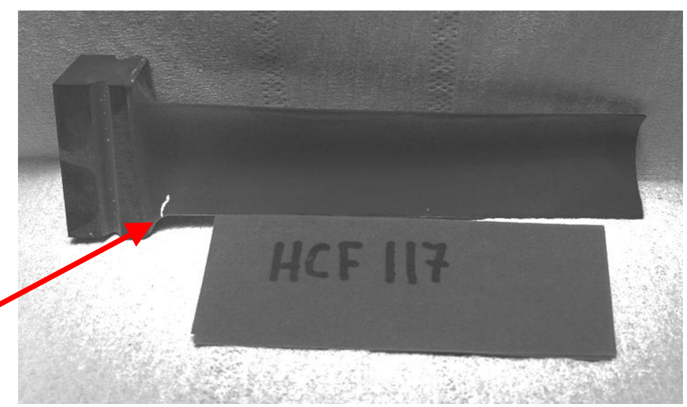
- Pre-oxidized 20 hrs at 650°C
- Machined by ECM to surface roughness R_a=1.6 μm
- Average fatigue limit: 400 MPa (58 ksi)



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 Aluminide manufactured with EBM:

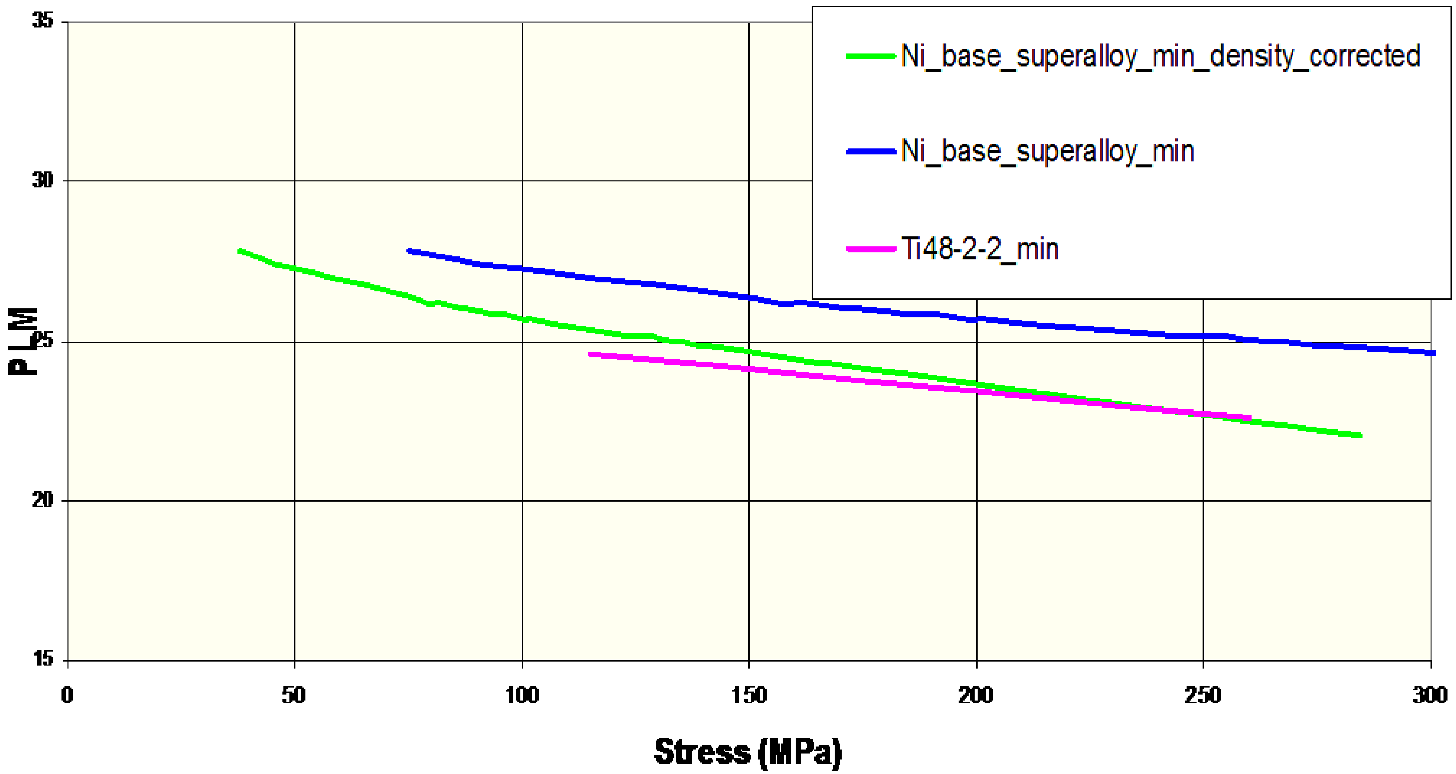
- 3D geometries (turbine blades) fabricated with proven process stability
- HIP eliminates residual porosity
- Complies with chemical spec. after 1% Al addition to powder
- Fine grain duplex microstructure after proper heat treatment
- Tensile properties equal to GE reference data
- HCF properties exceed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

Thank you!

Ulf Ackelid
Arcam AB

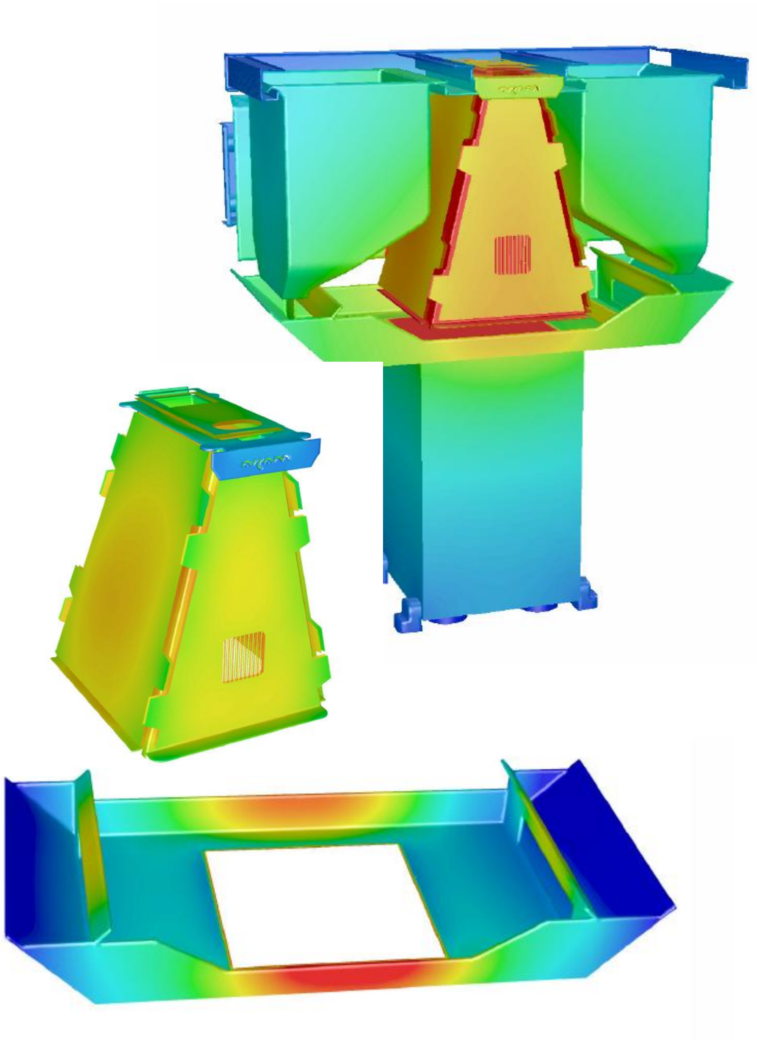
γ-TiAl with EBM
Creep properties

– Density corrected creep properties compared with Ni-base superalloys for use in LPT's last stages.

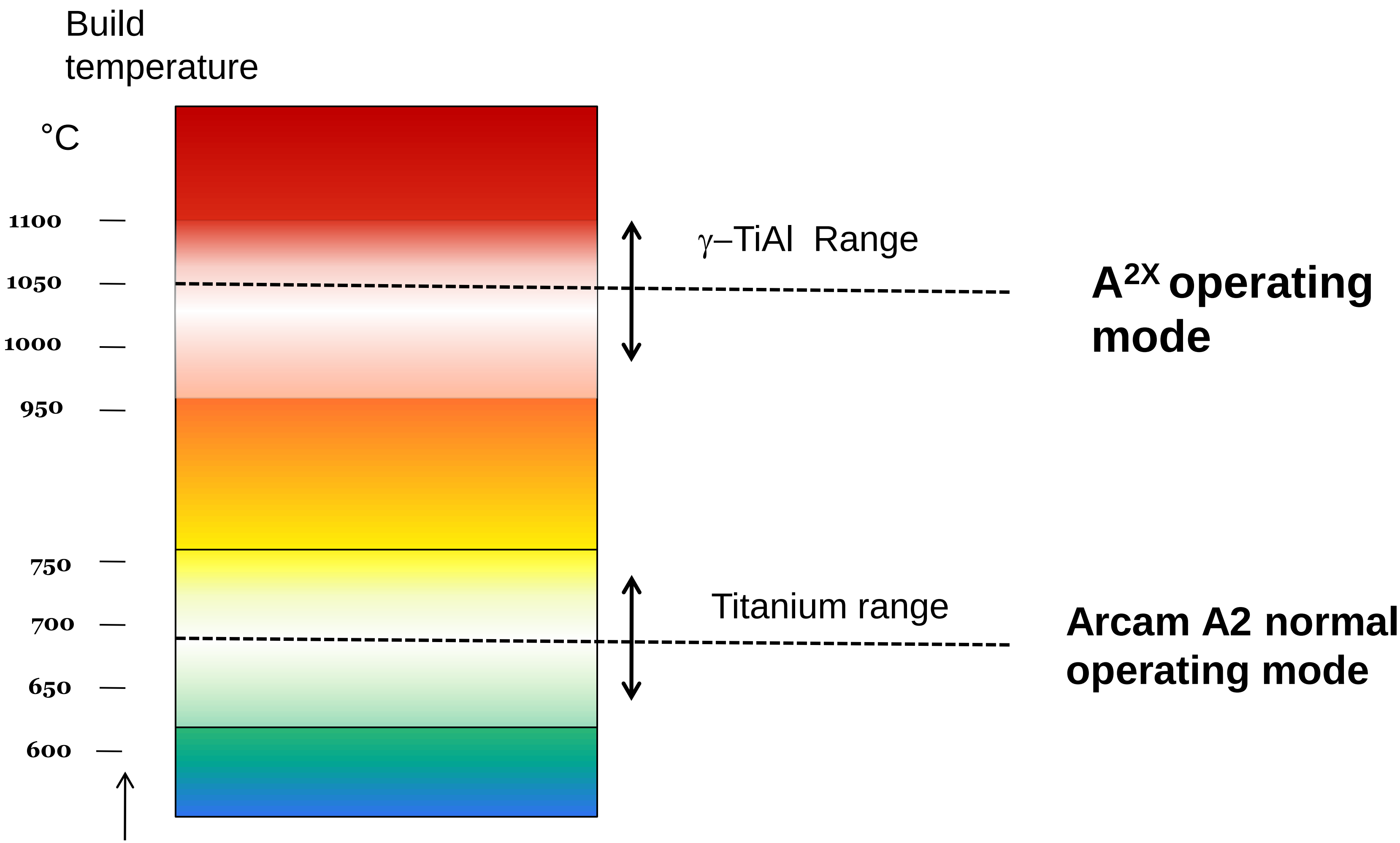


γ-TiAl with EBM
A^{2X} Heat load optimization

- 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.



γ-TiAl with EBM
A^{2X} Heat load optimization



γ-TiAl with EBM
A^{2X} 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