Heat Treatment of AM Parts by Hot Isostatic Pressing

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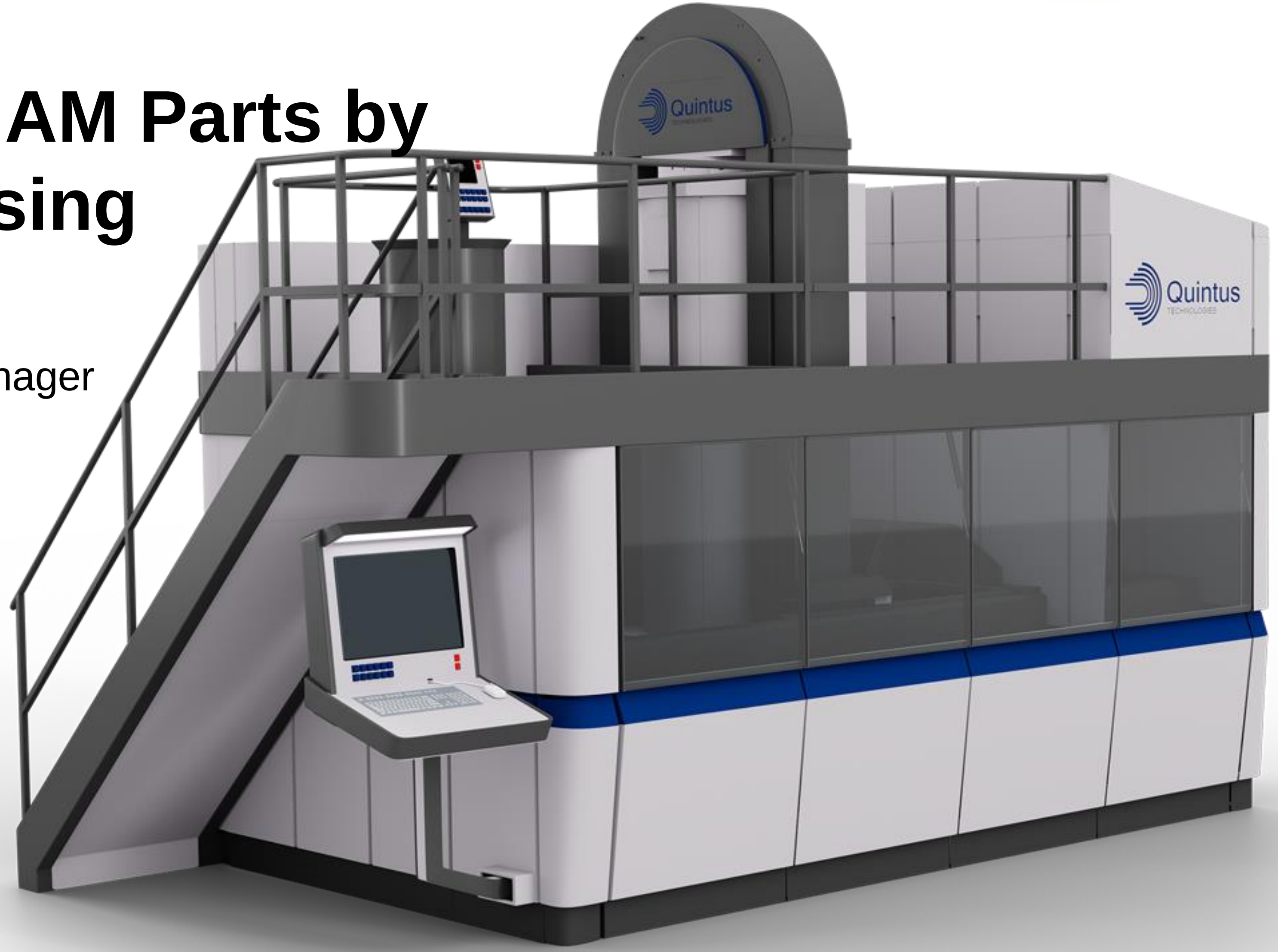

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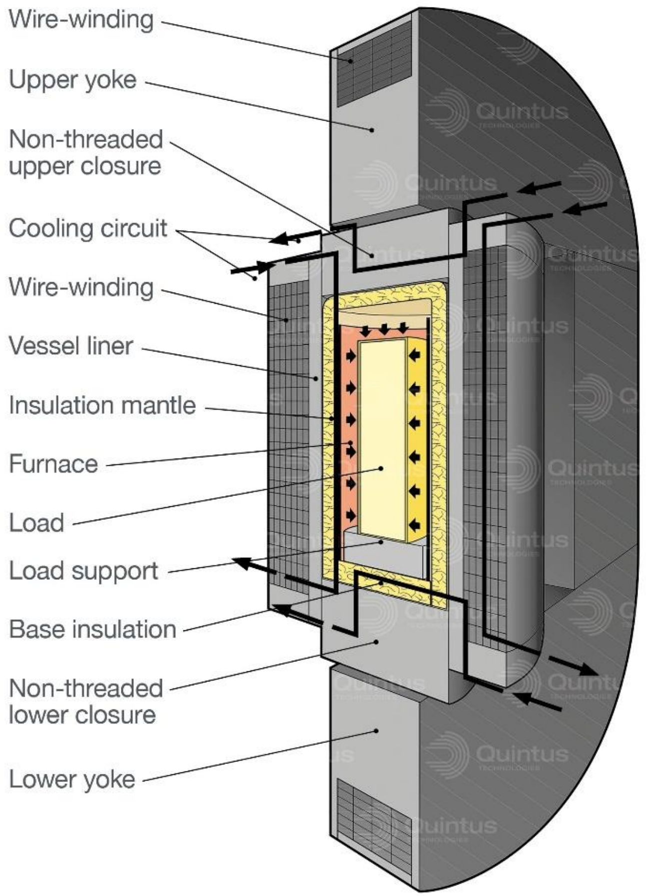
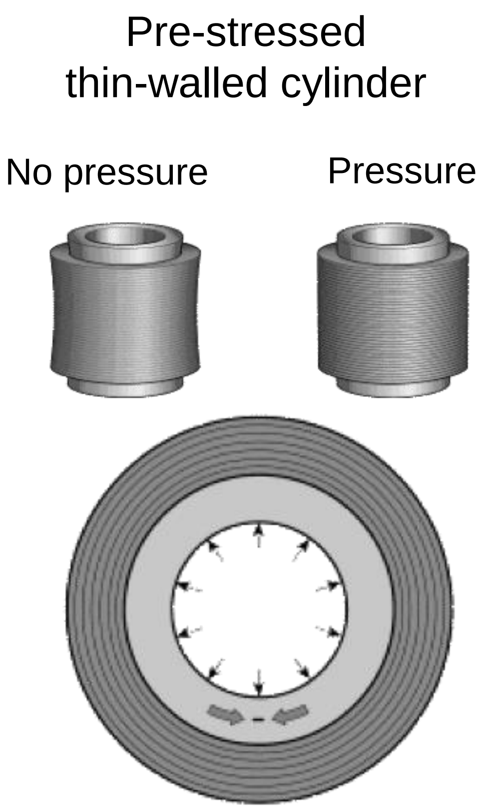
Isostatic Pressing

- Isostatic pressing is a forming process that applies equal pressure in all directions on a product, compacting the workpiece uniformly from all sides
  - This results in maximum uniformity of density and microstructure without the geometrical limitations of uniaxial pressing
- Hot Isostatic Pressing (HIP) is used to fully consolidate parts at elevated temperatures.
  - Temperatures are usually 500-2,000ºC (932-3,632ºF)
  - Pressures are usually 100-200 MPa (15,000 to 30,000 psi)
  - Gas used is typically argon
- The densification process is a combination of
  - Plastic deformation
  - Creep
  - Diffusion

Design of Quintus® pressure vessels - Core Technology





- Wire wound vessel gives a reduced footprint whilst decreasing the frequency needed for safety inspections
- The Patented Quintus URC® furnace technology includes a fan or nozzle for forced convection cooling
- High cooling rates allow combined heat treatment cycles

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What is Hot Isostatic Pressing used for?

- Refining a product
  - HIP is used as an extra process step to achieve better material properties

- Producing a product
  - HIP is used to produce the product ready for final post processing steps such as grinding or machining

- Densification of products produced by
  - Casting
  - Metal Injection Moulding (MIM)
  - Additive Manufacturing / 3D printing
  - Cladding
  - Diffusion bonding

- Compaction of powder
  - Powder billets
  - Tool steel
  - Near-Net-Shape (NNS)
  - Sputtering targets

Hot Isostatic Pressing

As-cast / MIM / 3D print

Powder Metallurgy

Hot Isostatic Pressing

Pores Eliminated

Near-Net-Shape Product

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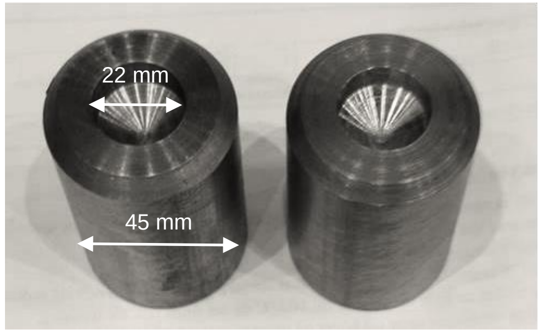
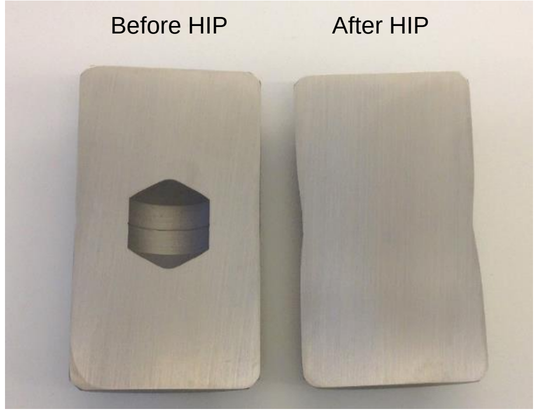
HIP of components with residual porosity

- HIP is used to remove porosity in metal parts
  - Internal porosity in Castings is always present after solidification due to material shrinkage
  - Micro porosity in MIM and 3D-printed components

- The combination of high temperature and high isostatic pressure will remove residual porosity
  - Temperature typically 80-90% of melting temperature
  - Pressure up to 2070 bar of Argon gas
  - At these pressures the gas acts as a liquid





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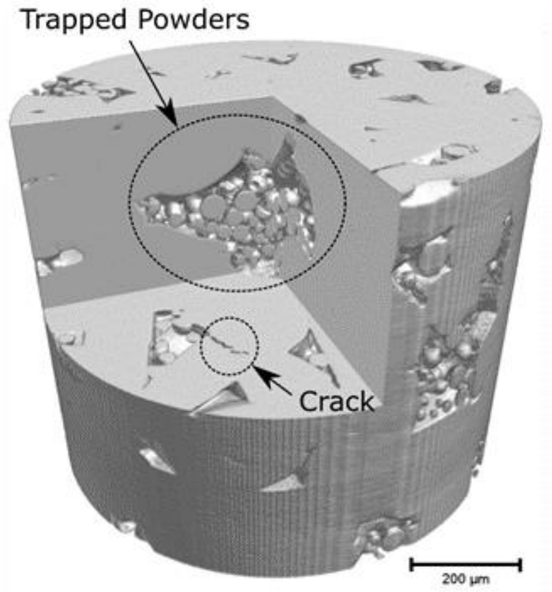
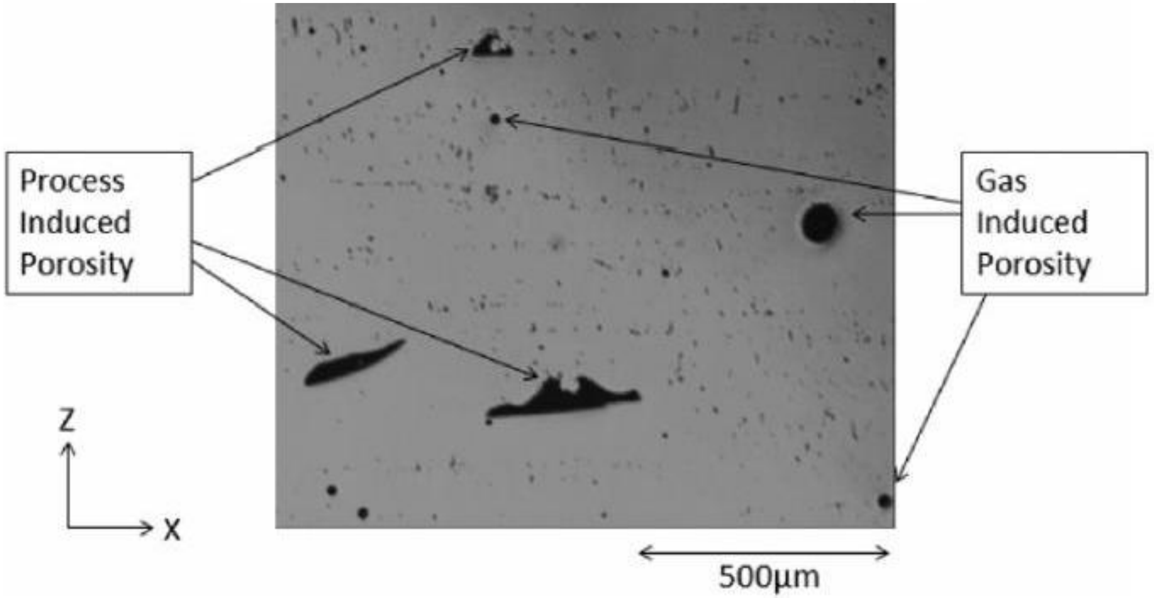
As-printed material

- Internal defects as-printed
  - Lack-of-fusion porosity
  - Gas porosity etc.
  - Oxides
  - Micro cracks
- Internal defects means
  - Stress concentrations
  - Crack initiation points
- Negative influence on
  - Fatigue
  - Ductility
  - Fracture toughness





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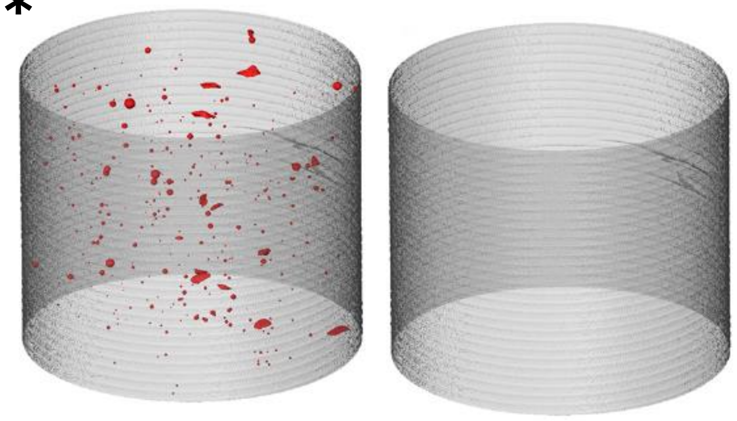
Why HIP?

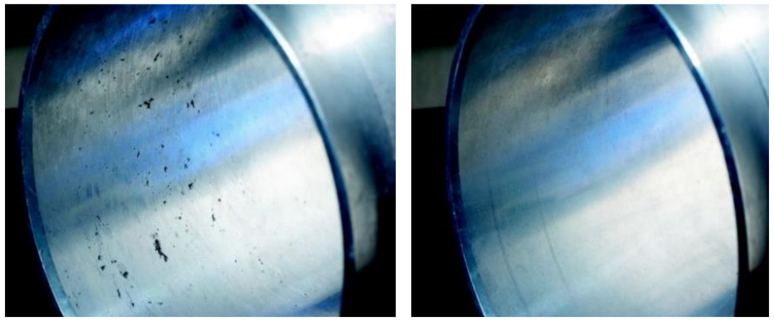
- Elimination of internal defects gives:
  - Elimination of stress concentrations and crack initiation points
- Superior material properties
  - Drastically increased fatigue life 10 – 100x
  - Increased ductility and fracture toughness
  - Reduced scatter
    - More predictive material properties
    - Increased lowest design values
- Improved machined/polished surface quality
  - Increased fatigue, corrosion, optical, sealing and esthetic properties

Before HIP After HIP

*



Before HIP After HIP



*Courtesy of: *Porosity regrowth during heat treatment of hot isostatically pressed additively manufactured titanium components*, S. Tammas-Williams et al, September 2016, Scripta Materialia 122:72–76

Variations in AM - Variables

Feedstock / Material

Chemistry

- Starting Chemistry
  - Variation from lot to lot
  - Variation within lot
  - Macro / micro segregation
- Recycling
  - Humidity or other Environmental Factors
  - Contamination, sieves, seals, brushes, etc.
  - Size distribution and morphology changes
  - Chemistry change, bulk and surface

Bed Density

- Particle Size Distribution
- Apparent / Tap Density
- Sintering

Thermal Profile

Process Parameters

- Start Temperature
  - Bottom thermocouple placement critical
- Preheat Temperature
  - Based on geometry
  - Beam Focus value (not calibrated)
  - Line Order
  - Raster Speed
  - Beam Current
- Melt Scheme
  - Scan Strategy, line, point, area melting
  - Beam current, speed, focus, etc. changes with geometry due to physics
- Post heat
  - Same as preheat, but incorporates melt, geometry and overall current
  - Between parts or at the end of layer

Geometry

Feedstock

Execution

Machine to Machine Variability

- Different software version
- Different power supplies, filaments, e- gun designs, focusing coils, etc.
- Operating environments – temperature, humidity, magnetic fields, etc.

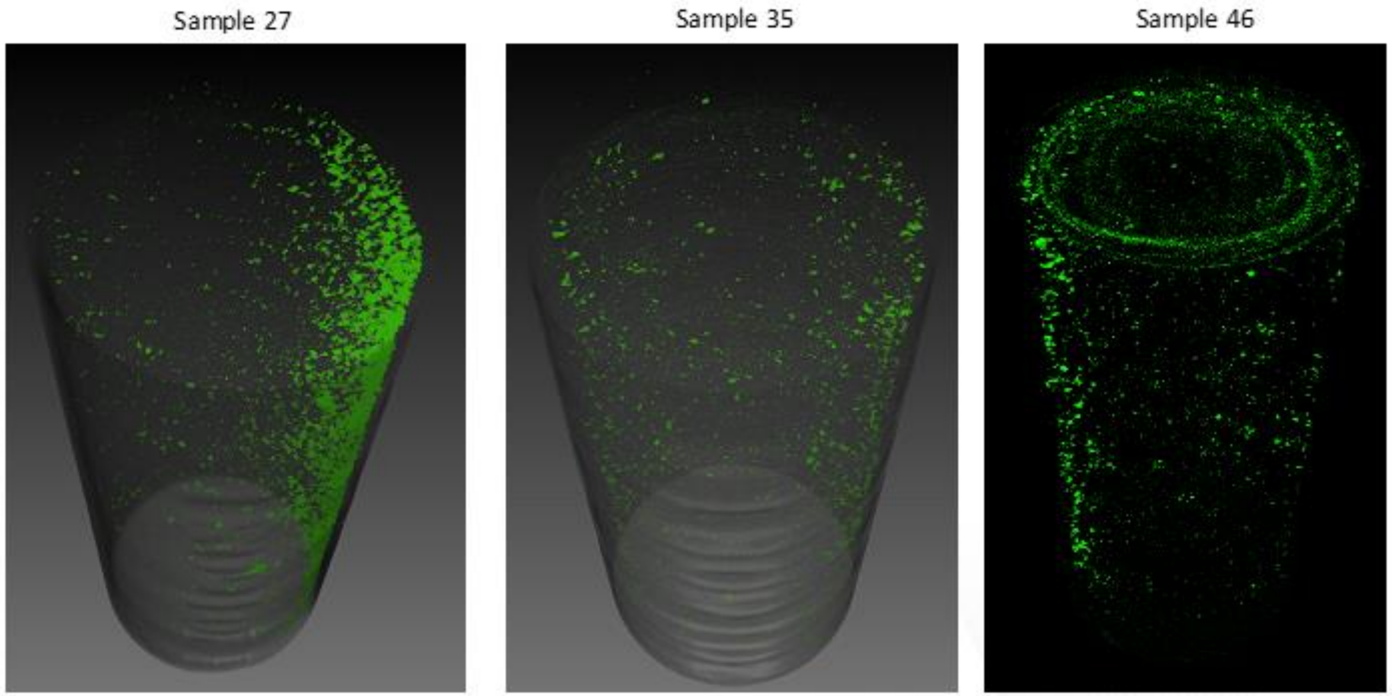
Process Variability

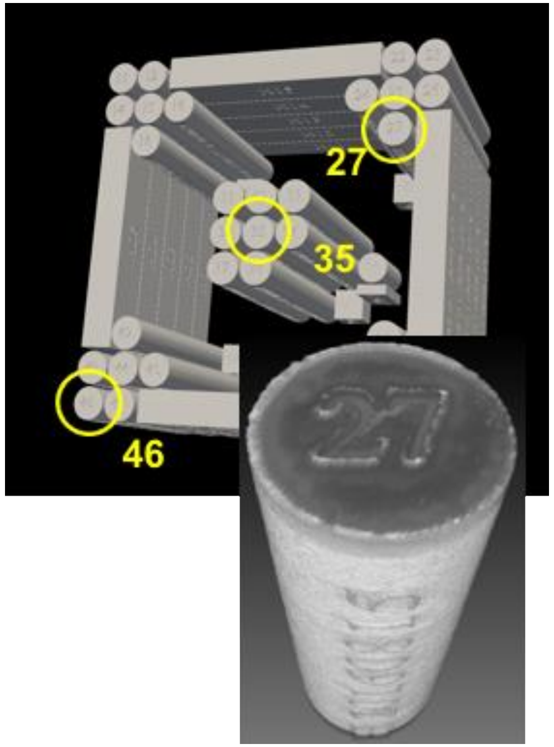
- Operator
  - Variation in personnel
  - Steps in Magics Software
    - Support Structure Generation
    - Additional parts for heat sinks
  - How builds are loaded in machine
    - Order
    - Grouping of parts
- Location
- Maintenance
  - Different Support Staff from Arcam

Courtesy of Oak Ridge National Laboratory

Variations in AM – Build plate position

- Example (EBM T64):
  - Sample position on the build plate =>
  - Variation in porosity





Courtesy of Oak Ridge National Laboratory

Typical AM operations

Pre-Processes

- Design
- Shrinkage calculation
- Powder selection
- Powder sourcing
- Powder handling
- Cleaning of AM system
- Evacuation / Purging
- Pre-heating

Printing

- Spreading powder
- Printing contour
- Printing hatch pattern
- In-situ monitoring
- Recycling of powder

Post processes

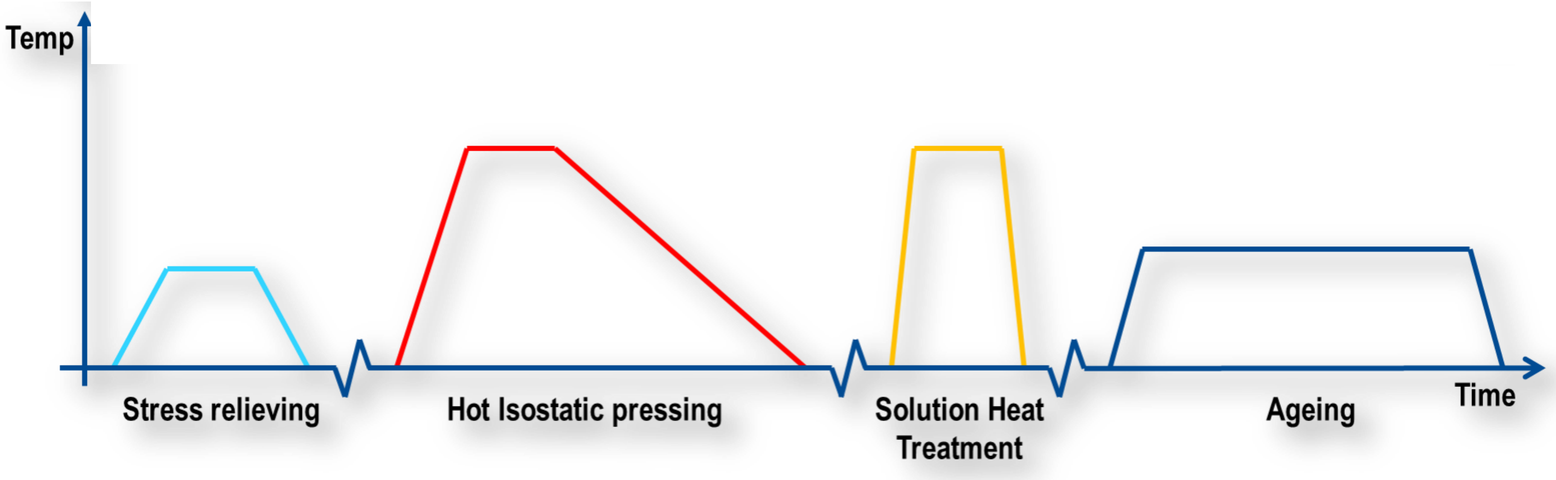
- (Curing)
- (De-binding)
- (Sintering)
- **Stress relief**
- Part removal
- Support removal
- Recycling of build plate
- Cleaning
- **HIP**
- **Heat treatment**
- Machining
- Chemical milling
- Abrasive flow machining
- Sand blasting
- Short peening
- Coating

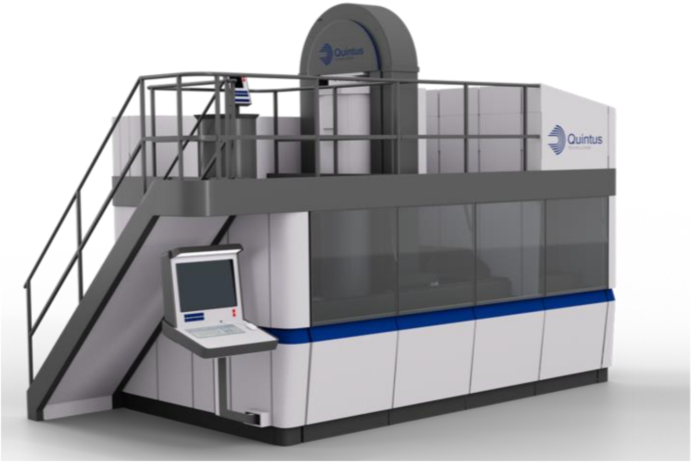
Quality control

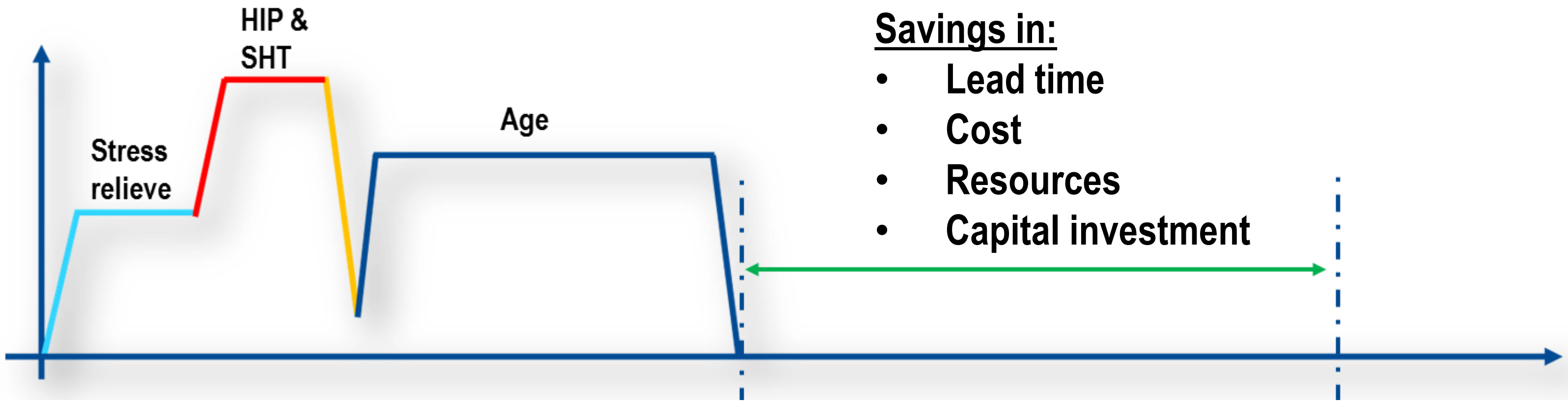
- CT scanning
- Inspection
- Powder management
- Property checks

(Binder Jet Process)

High Pressure Heat Treatment

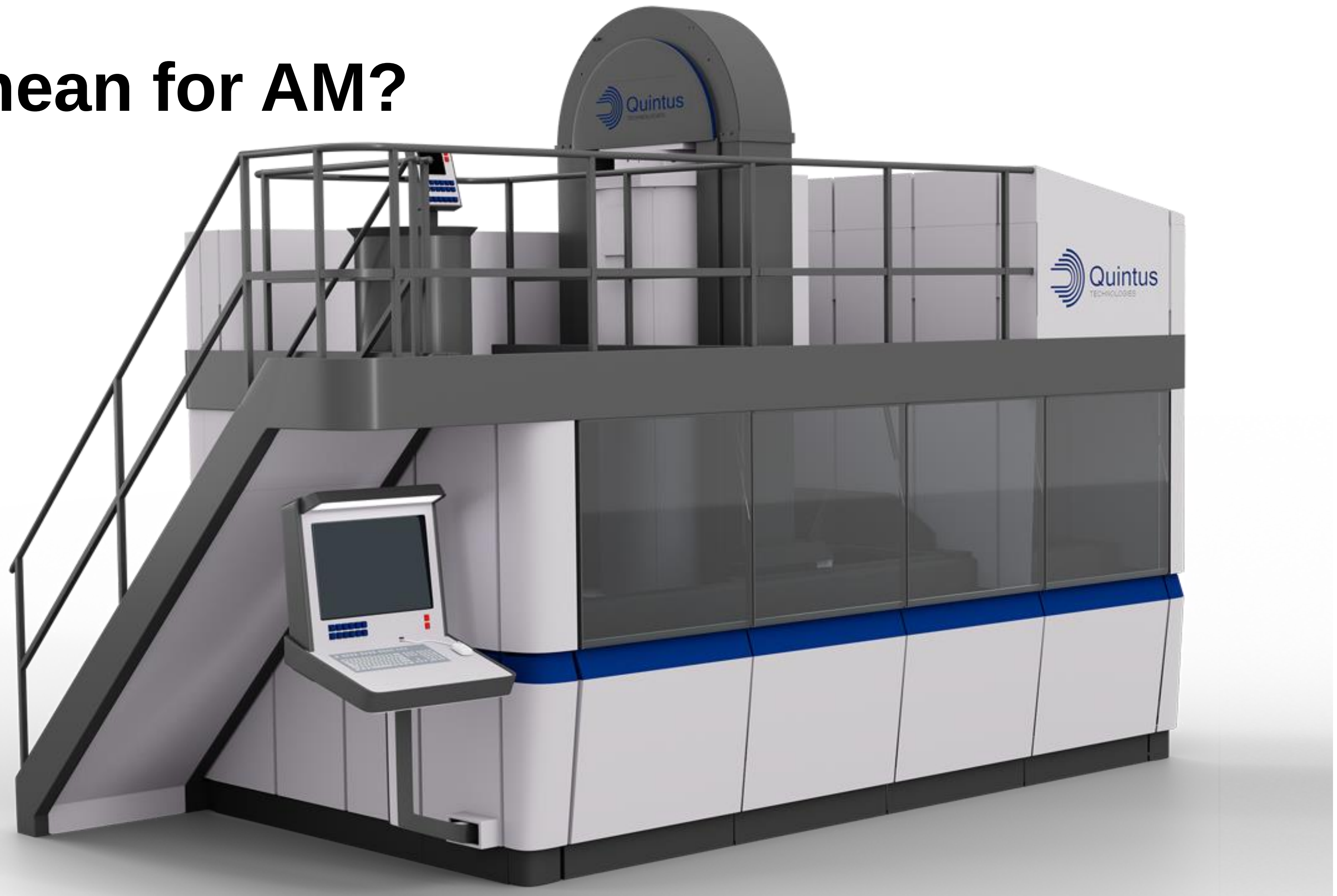




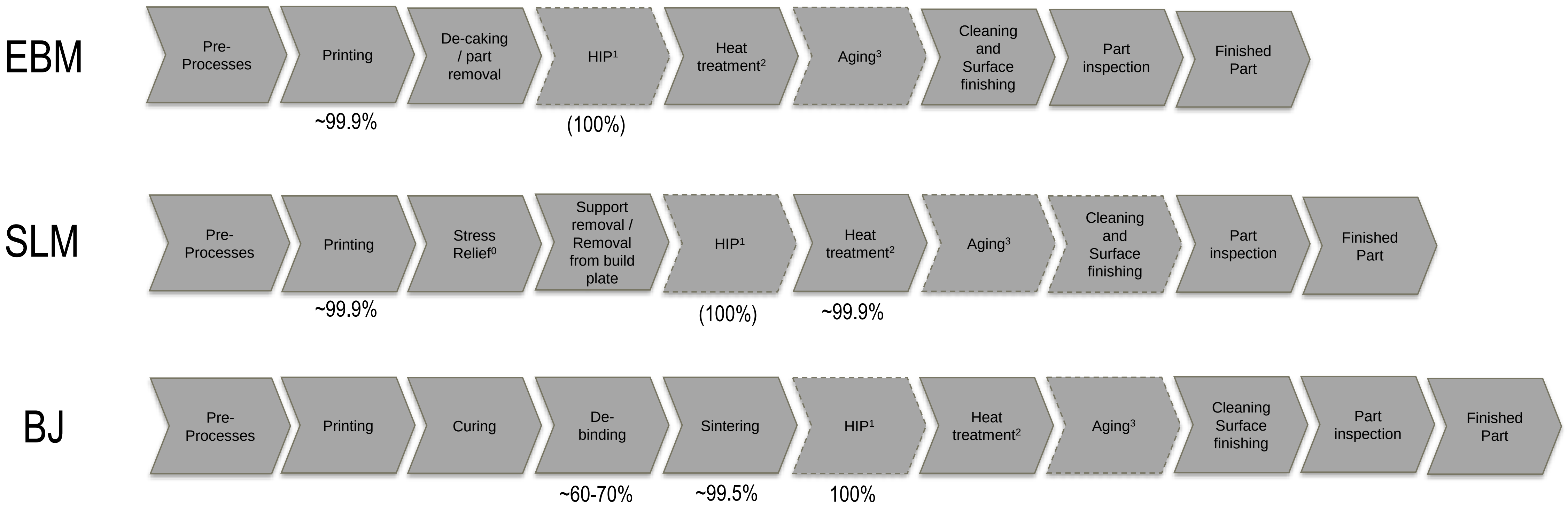


Savings in:
- Lead time
- Cost
- Resources
- Capital investment

What does this mean for AM?

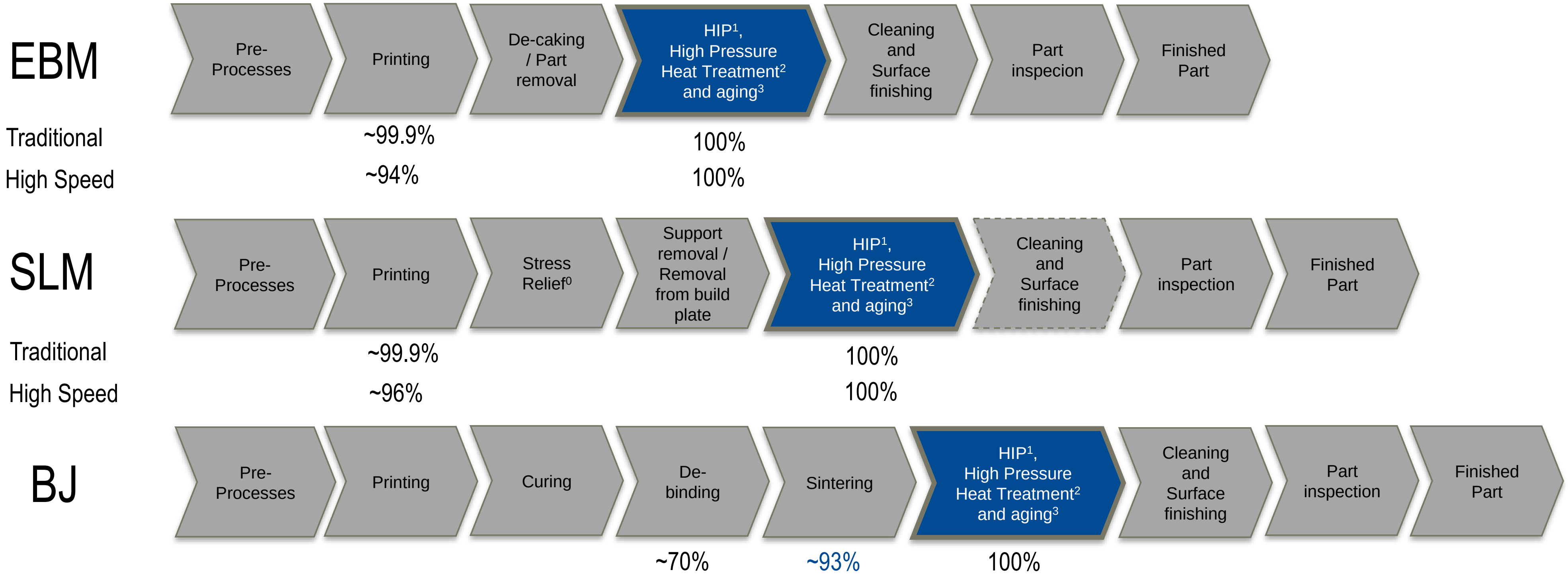


Typical AM process flow



[0] Removal of stresses created by printing process
[1] Removal of porosity and improvement of fatigue resistance
[2] Adjustment of material properties
[3] For specific alloys

Possible process flow



[0] Removal of stresses created by printing process
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Laser PBF Factory of the Future

[0] Removal of stresses created by printing process
[1] Removal of porosity and improvement of fatigue resistance
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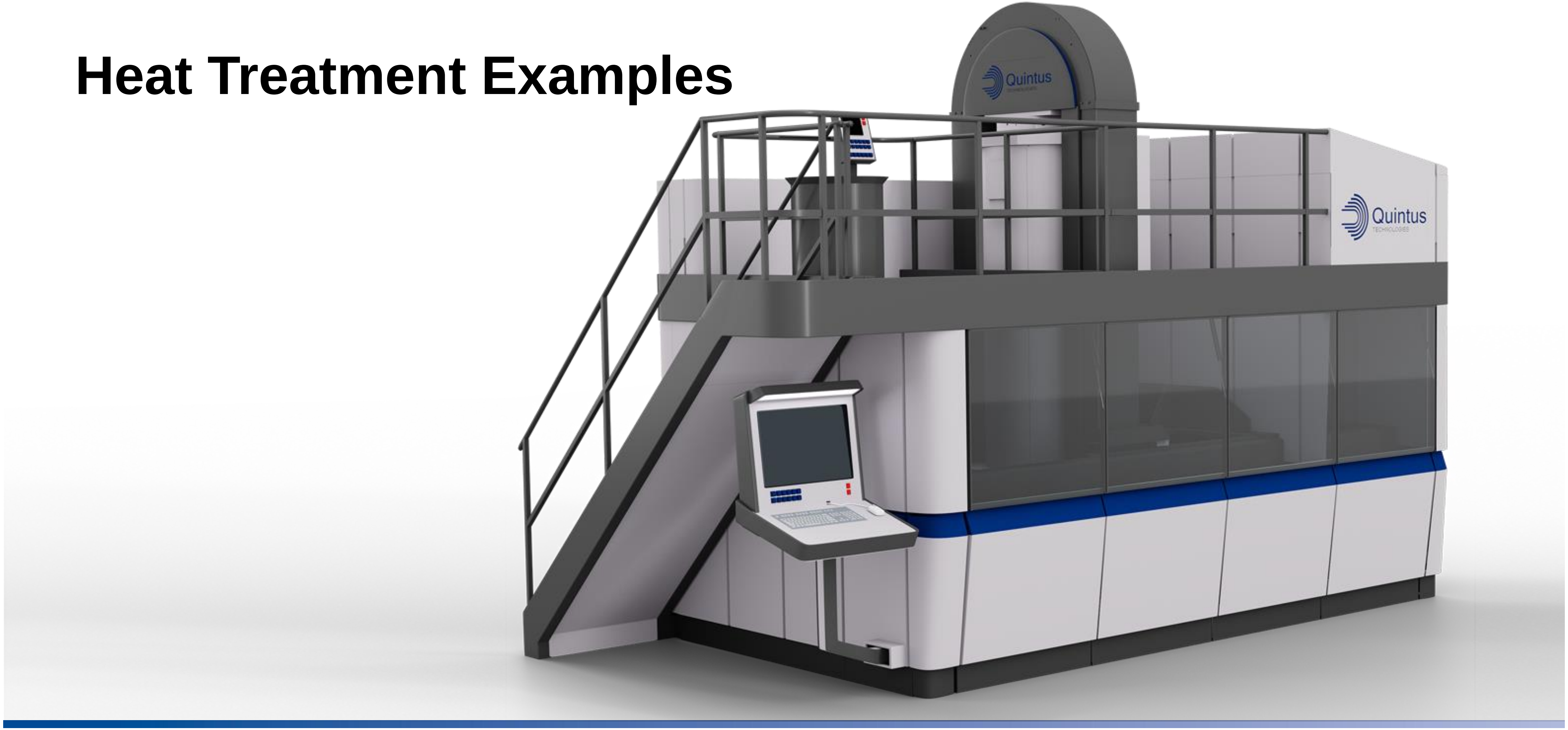
Heat Treatment Examples



Comined HIP and heat treatment cycle for In718

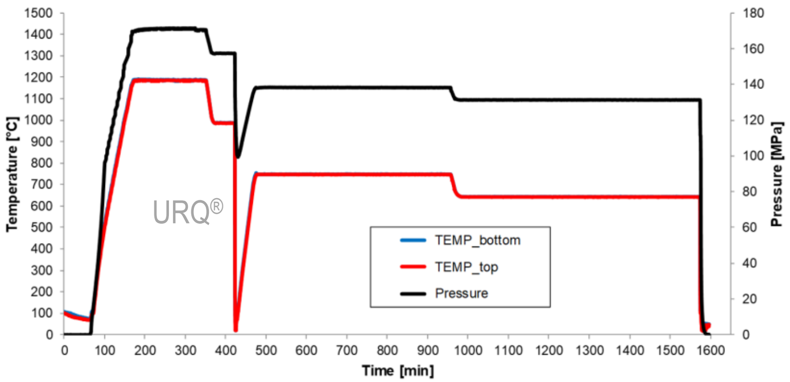
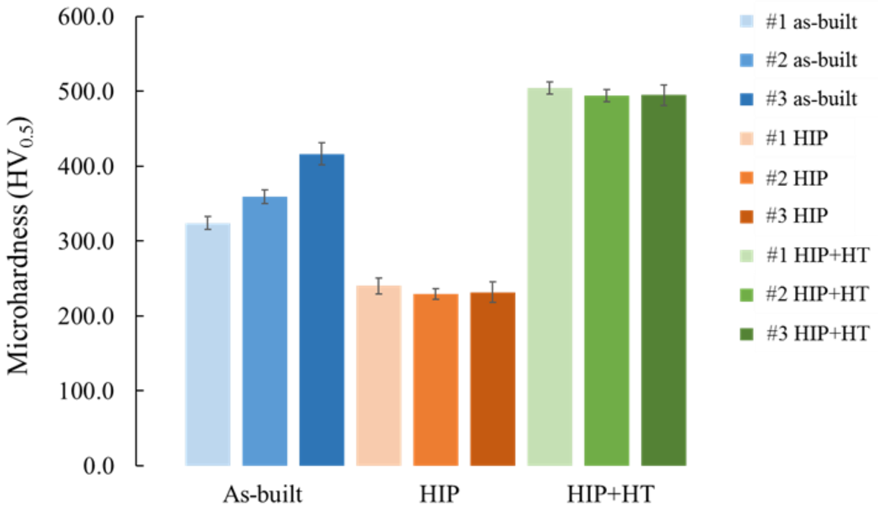


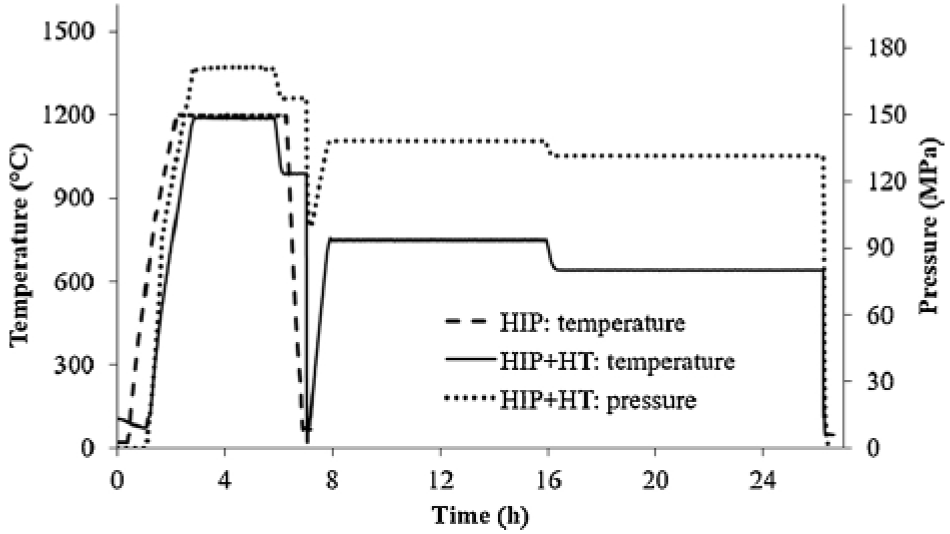
Figure 6 – Combined HIP and heat treatment cycle for In718 performed in a HIP unit



- The typical HIP cycle for PBF IN718 according to ASTM F3055- 4a that has been combined with the typical heat treatment for this alloy including solutionizing, rapid cooling and a dual temperature ageing according to AMS5663N. As can be seen the full process can be performed in the HIP.
  - It is also possible to take the parts out after the combined HIP, solutionize and rapid cooling step and perform the 18+ hour ageing in another furnace if that is more efficient.

- Micro-hardness measurements showed a benefit of combining the cycles

Recent results confirm the same



Post-treatment	Cycle
HIP	1200 °C/ 120 MPa/ 4 h/ RC (approximately 42 °C/min)
HIP + HT	1185 °C/ 170 MPa/ 3 h/ FC (approx. 13 °C/min) to solutionizing temperature (980 °C) Solution treatment (ST): 980 °C/ 157 MPa/ 1 h/ RC to RT Aging: 740 °C/ 138 MPa/ 8 h/ FC to 635 °C/ 131 MPa/ 10 h/ RC to RT

Note: FC, RC, and RT denote furnace cooling, rapid cooling, and room temperature, respectively.

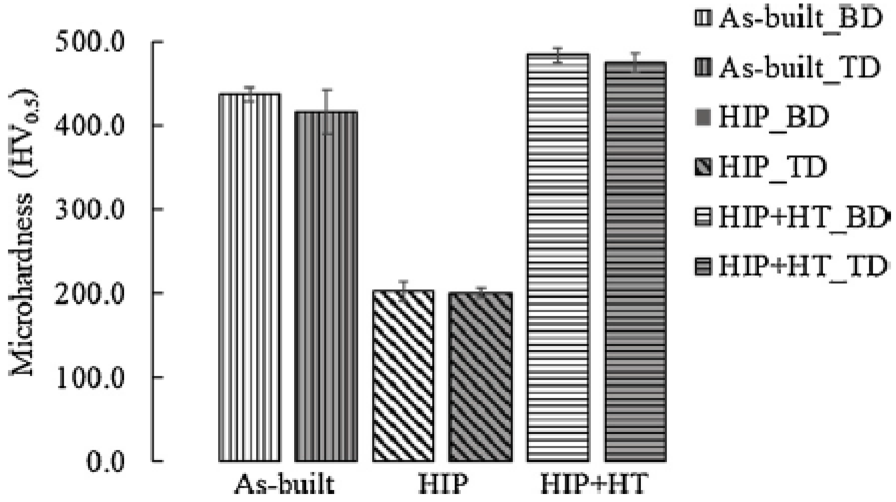


Fig. 17. Microhardness of as-built and post-treated specimens, where BD and TD denote build and transverse direction, respectively.

Effect of post-treatments under hot isostatic pressure on microstructural characteristics of EBM-built Alloy 718

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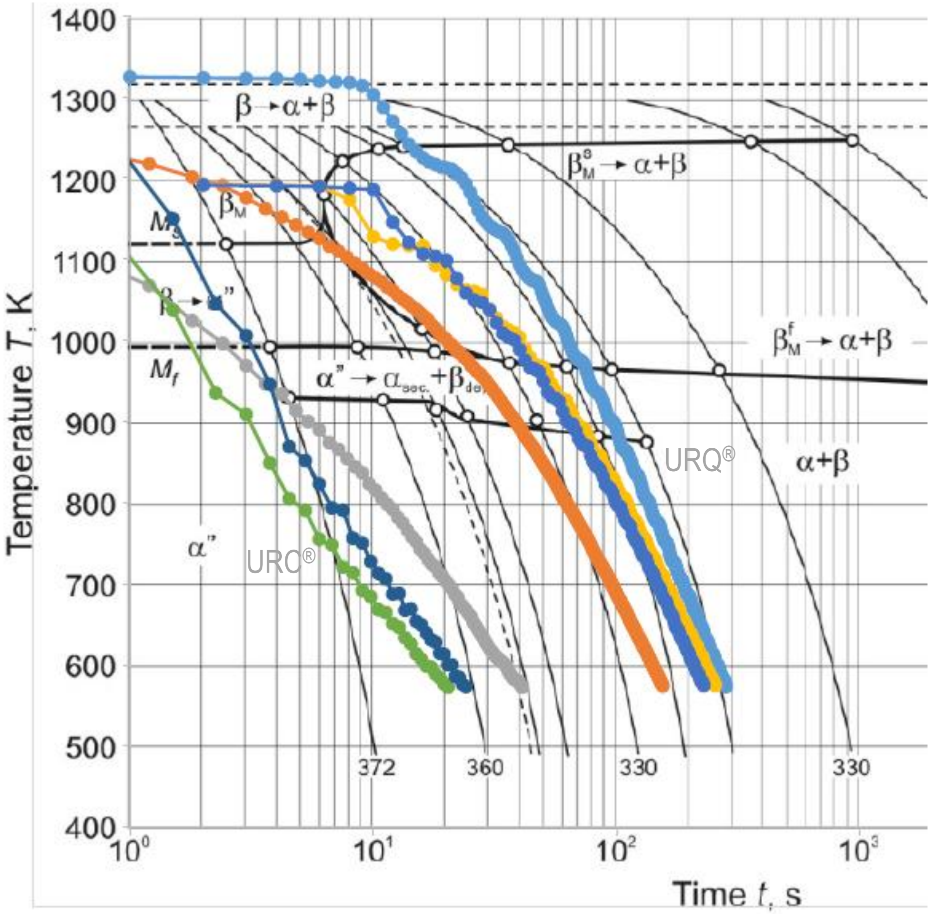
[c] Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden

Direct quench from HIP-temperature from β-region

- Direct quench from HIP-temperature from β-region
  - Heat treatment specifications for TiAl6V4 suggest water quench for maximum strength.
  - Literature and CCT-diagram suggest quench rates in the range of 500-3000 K/min during the phase transition (900° → 750°C)

- Experiment:
  - TiAl6V4 samples were quenched by URC® /URQ®. Gas quench rates in the range of 300-6000 K/min were recorded.
  - Fine acicular ferrite with UTS >1000MPa was reproduced reliably.



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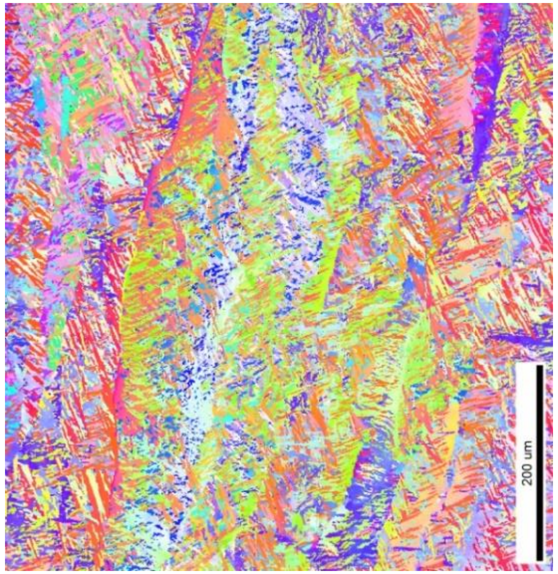
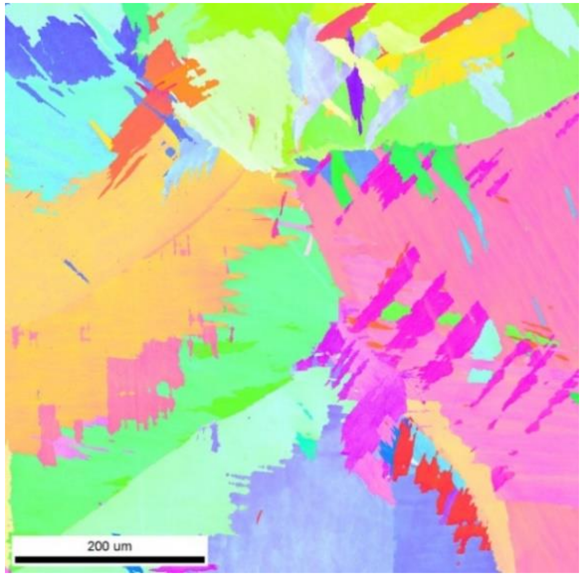
HIP above β-transus temperature HIP for Ti-6Al-4V

- Anisotropic microstructure and properties
- Possibility to erase variations and anisotrophy with above β-transus HIP (e.g.1100 °C)?
  - Yes, but fast cooling needed for mechanical properties
- Ongoing work at ORNL

As-printed columnar structure



After HIP with quench equiaxed structure



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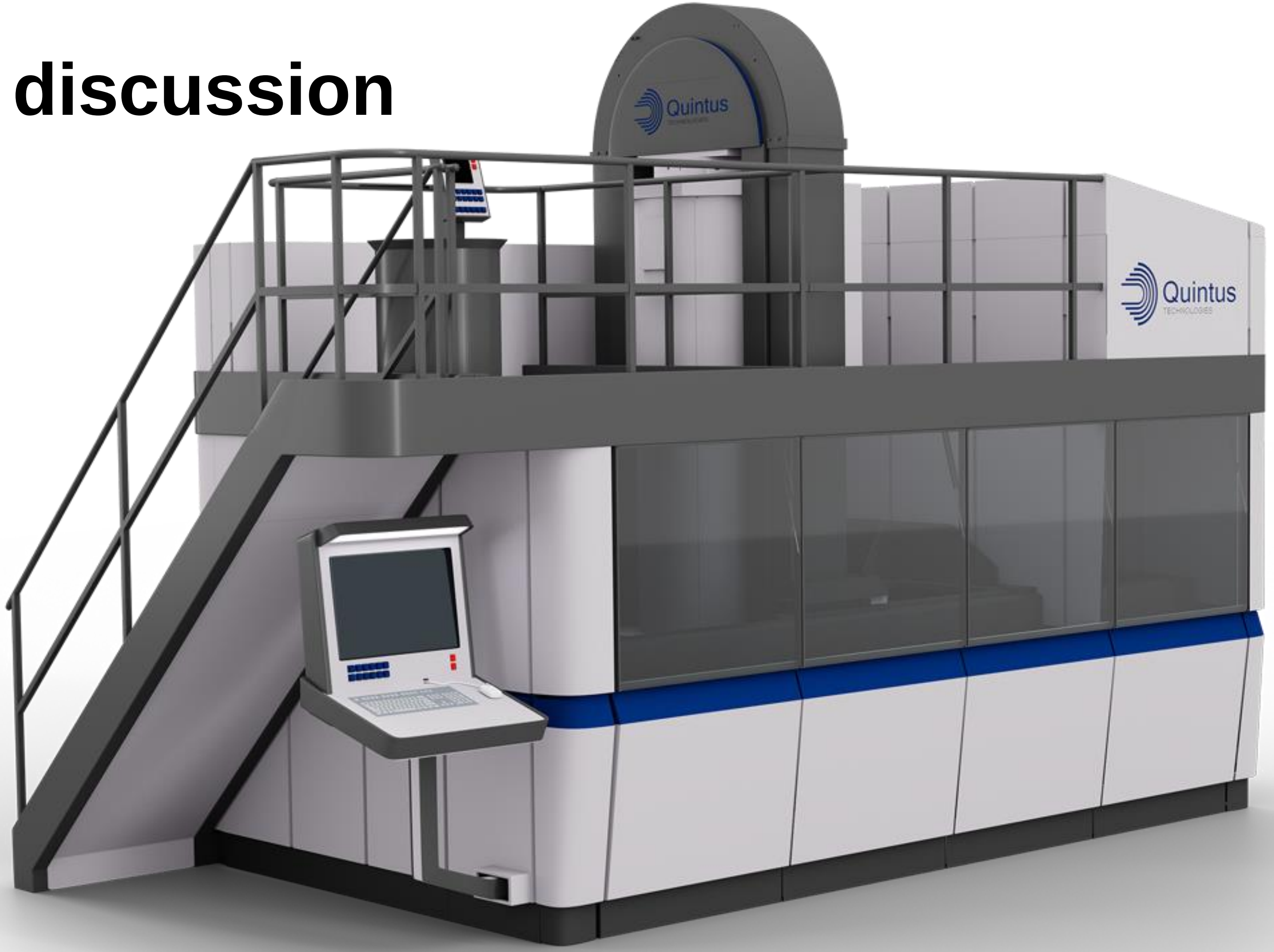
Conclusions and discussion



Conclusions and discussion

- Heat treatment cycles can be included in the HIP cycles used for AM parts.
- The total AM build process time can be reduced using high pressure heat treatment.
- Improved mechanical properties and the predictability of processes facilitates a robust move from prototyping to production.
- Lean AM Manufacturing™ can be facilitated through the reduction of process steps and improved document handling with modern HIP equipment at the centre of the production chain.

Thank you for your attention

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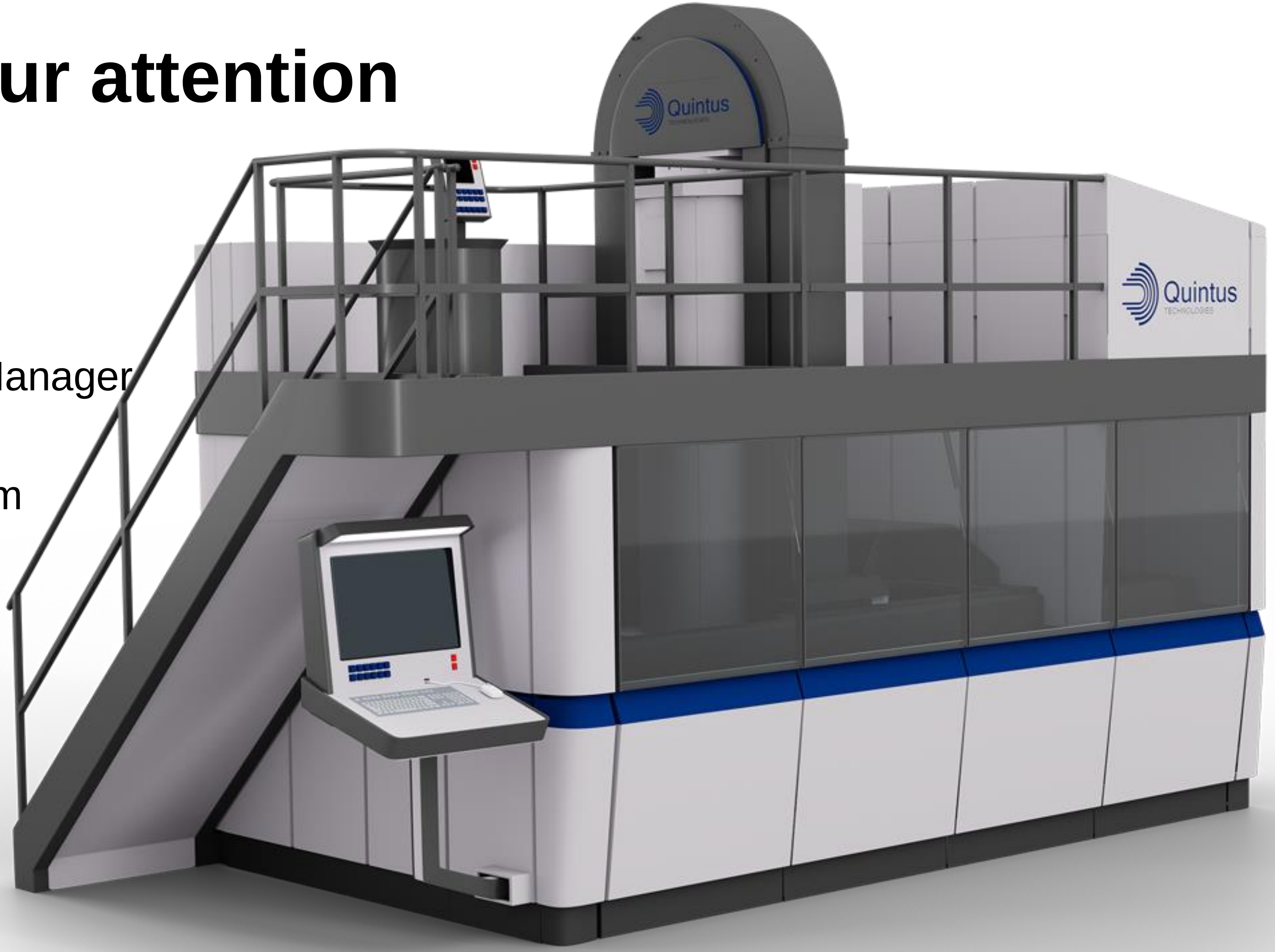

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