Hot Isostatic Pressing – Post-processing of AM components for critical applications

Hans Södervall
Business Development Manager
Advanced Material Densification

Quintus TECHNOLOGIES

Outline

- History of HIP
- Hot isostatic pressing
- The effect of HIP
- The HIP press and system safety
- High pressure heat treatment
- HIP in Additive Manufacturing
- Summary and Questions

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The Origin of HIP

- Hot isostatic pressing was developed at Battelle Memorial Institute, Columbus Laboratories, Columbus, Ohio in 1955.
- The HIP (originally called gas-pressure bonding) was used in an isostatic diffusion bonding process for cladding of nuclear fuel elements.
- Initially hot wall HIP, max. temperature 830°C & pressure 69 MPa

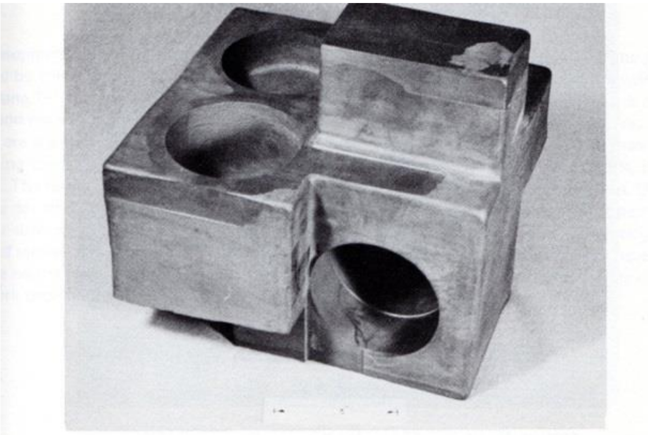
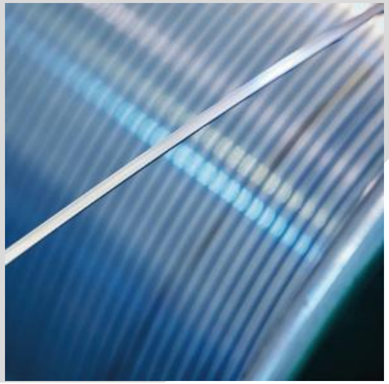


FIGURE 19. COMPLEX BERYLLIUM PREFORM FORMED BY HIP. INTERNAL HOLES WERE FORMED BY DEFORMABLE TOOLING

Courtesy of: Prof. Olle Grinder, PM Technology AB (deceased)

Quintus Technologies – the origin

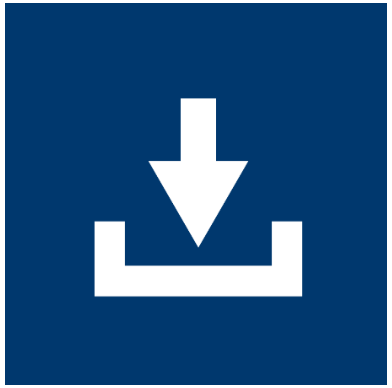
INNOVATION LEGACY FROM 1950



PIONEERING THE INDUSTRY

MATERIAL DENSIFICATION

SHEET METAL FORMING



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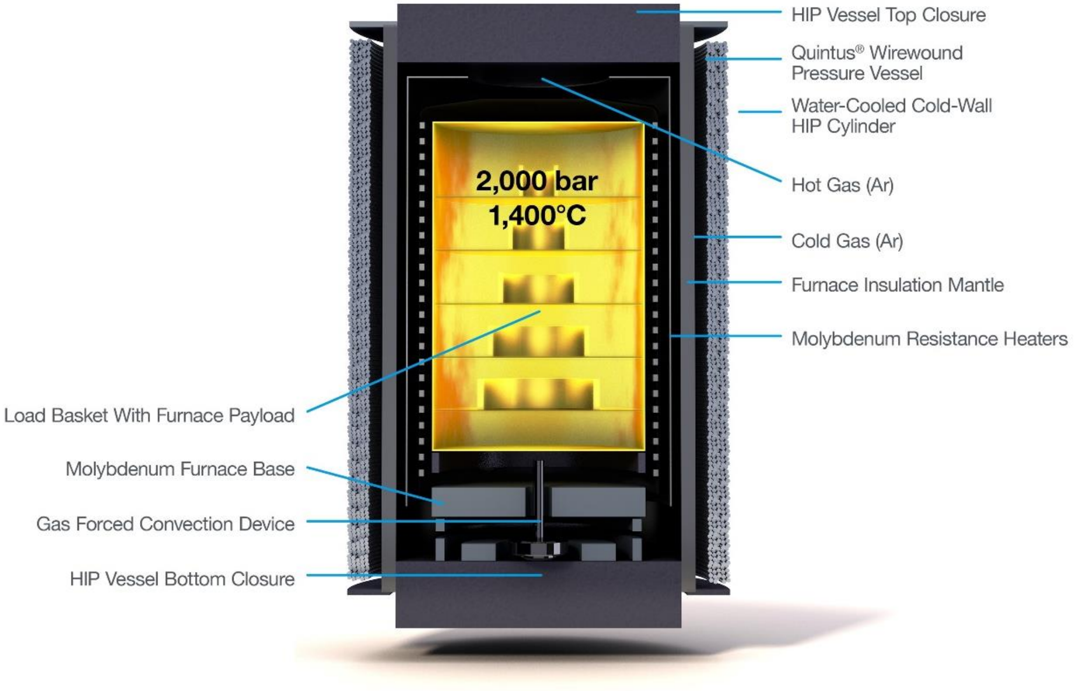
Hot Isostatic Pressing principles

Isostatic Pressing

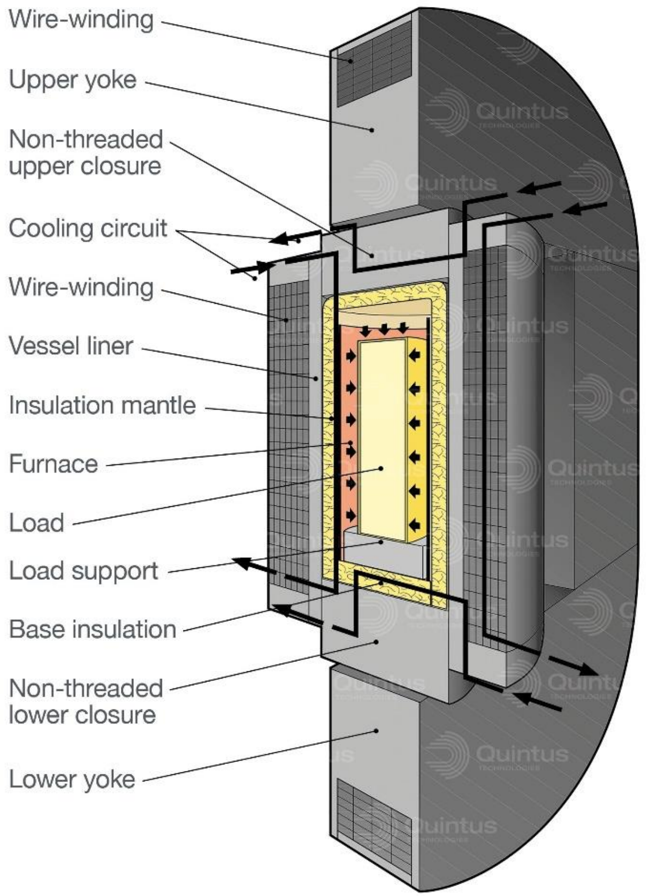
- Isostatic pressing is a forming process that applies equal pressure in all directions on a product, compacting the workpiece uniformly from all sides
  - This results in maximum uniformity of density and microstructure without the geometrical limitations of uniaxial pressing

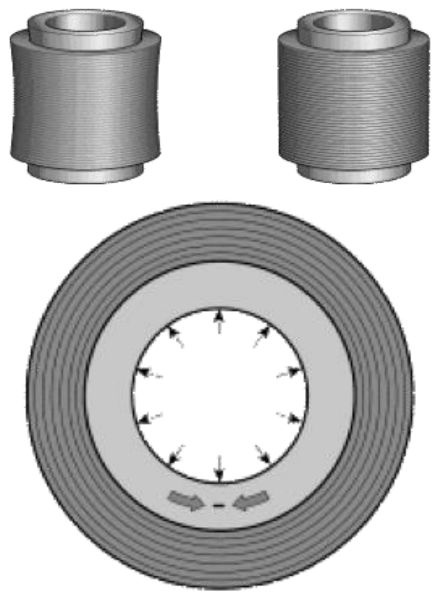
- Hot Isostatic Pressing (HIP) is used to fully consolidate parts at elevated temperatures.
  - Temperatures are usually 500-2,000ºC (932-3,632ºF)
  - Pressures are usually 100-200 MPa (15,000 to 30,000 psi)
  - Gas used is typically argon

- 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

What is Hot Isostatic Pressing used for?

- Densification of products produced by
  - Additive Manufacturing / 3D printing
  - Casting
  - Metal Injection Moulding (MIM)
  - Cladding
  - Diffusion bonding
- Compaction of powder
  - Powder billets
  - Tool steel
  - Near-Net-Shape (NNS)

Courtesy of: MTC Powder Solutions

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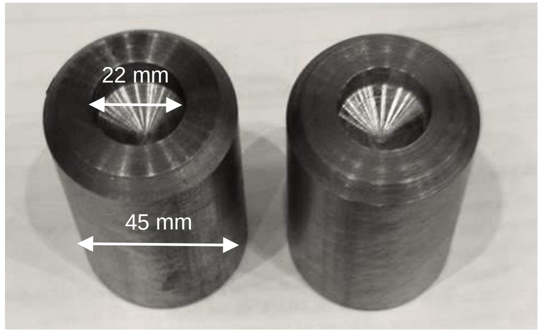
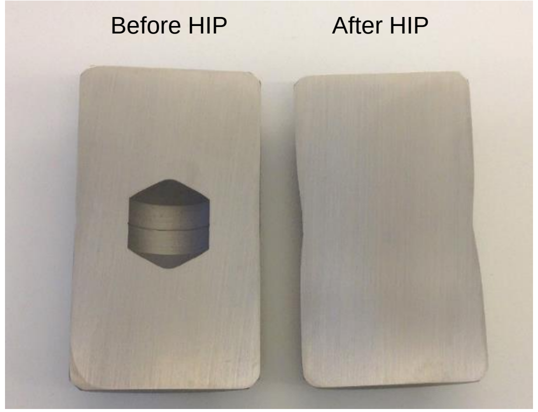
What does Hot Isostatic Pressing achieve?

- A 100% dense material
- Improved material properties
  - Fatigue
  - Ductility
- Reduced scatter in material properties
  - Predictive component life
  - Low weight design
- Decreased scrap loss





The effect of HIP

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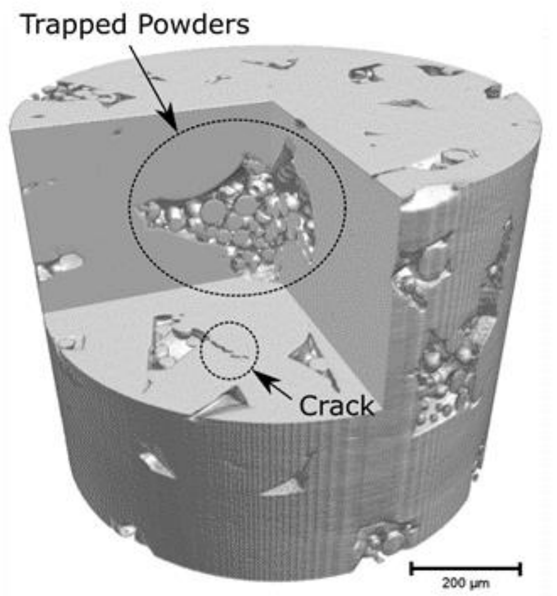
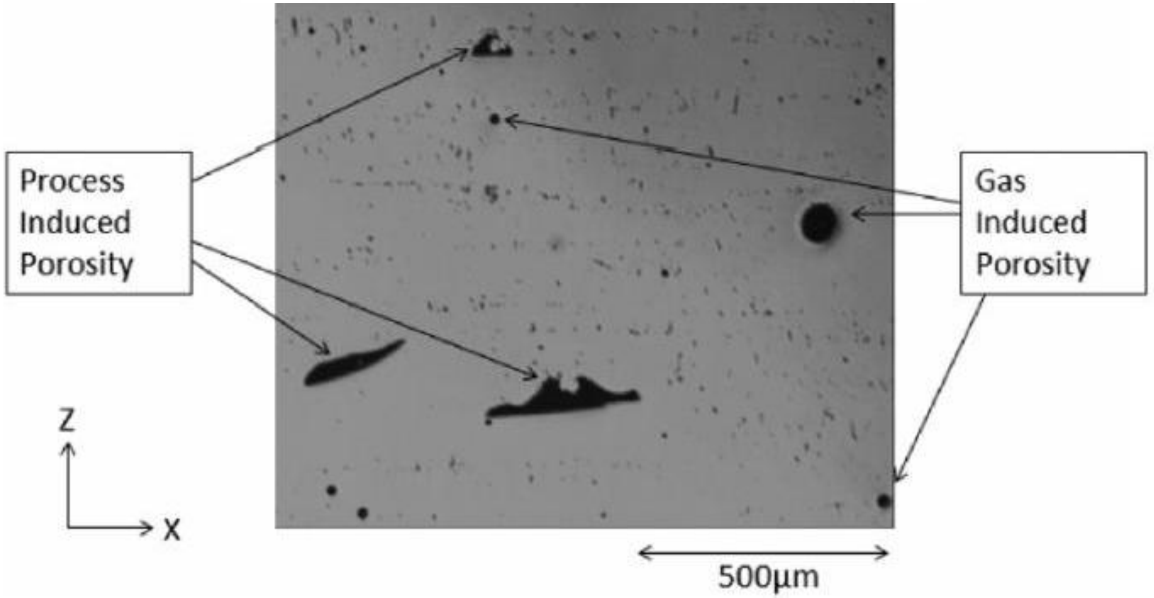
As-printed material

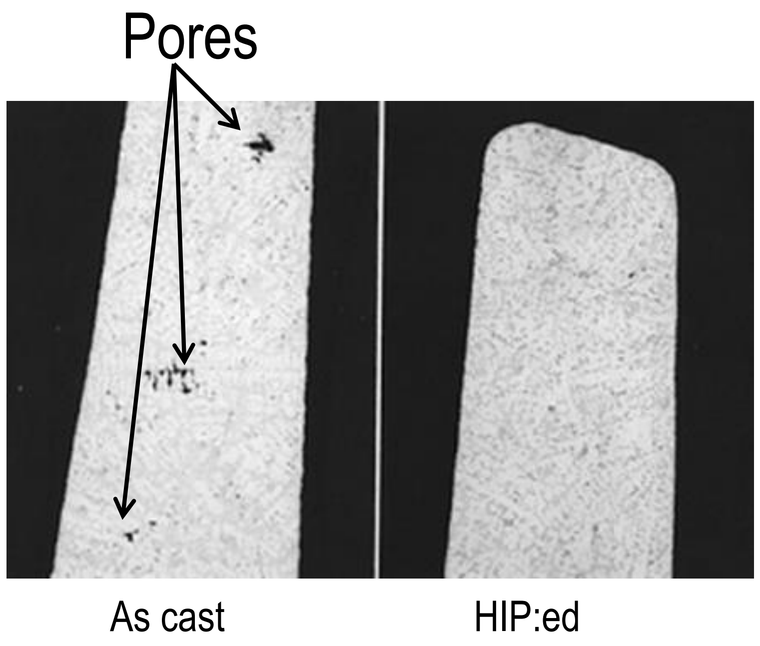
- Internal defects as-printed
  - Lack-of-fusion porosity
  - Gas porosity etc.
  - Oxides
  - Micro cracks
- Internal defects
  - Stress concentrations
  - Crack initiation points
- Negative influence on
  - Fatigue
  - Ductility
  - Fracture toughness





Effect of pore elimination

- With the pores removed the mechanical properties improve
  - Increased yield and tensile strength
  - Increased ductility
  - Much improved fatigue life, often by 10-100x
  - Lowers the scatter level of the properties
- Improved machined surface quality
- Improved form stability
  - Less thermal stresses
- Lower rejection rates
  - Saves poor quality components



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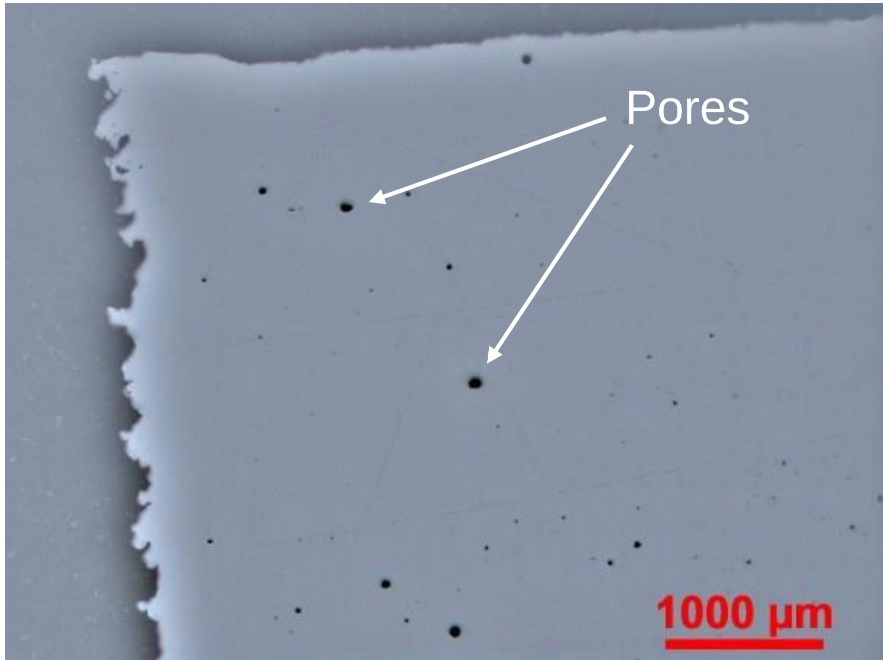
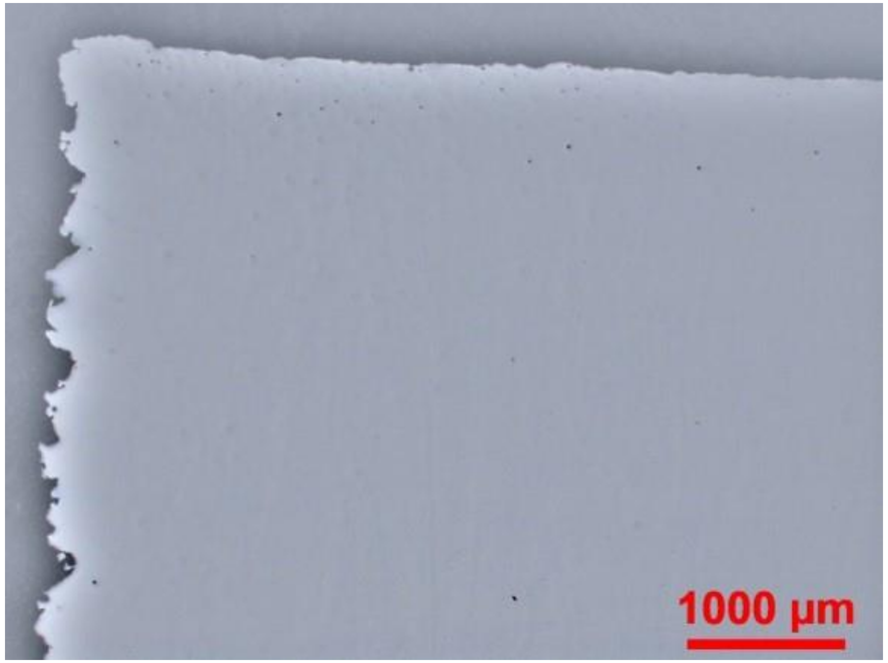
Example: EBM AM 316L

- Powder bed fusion gives relatively high as-printed densities
  - HIP still have a large effect on the fatigue properties

As-built

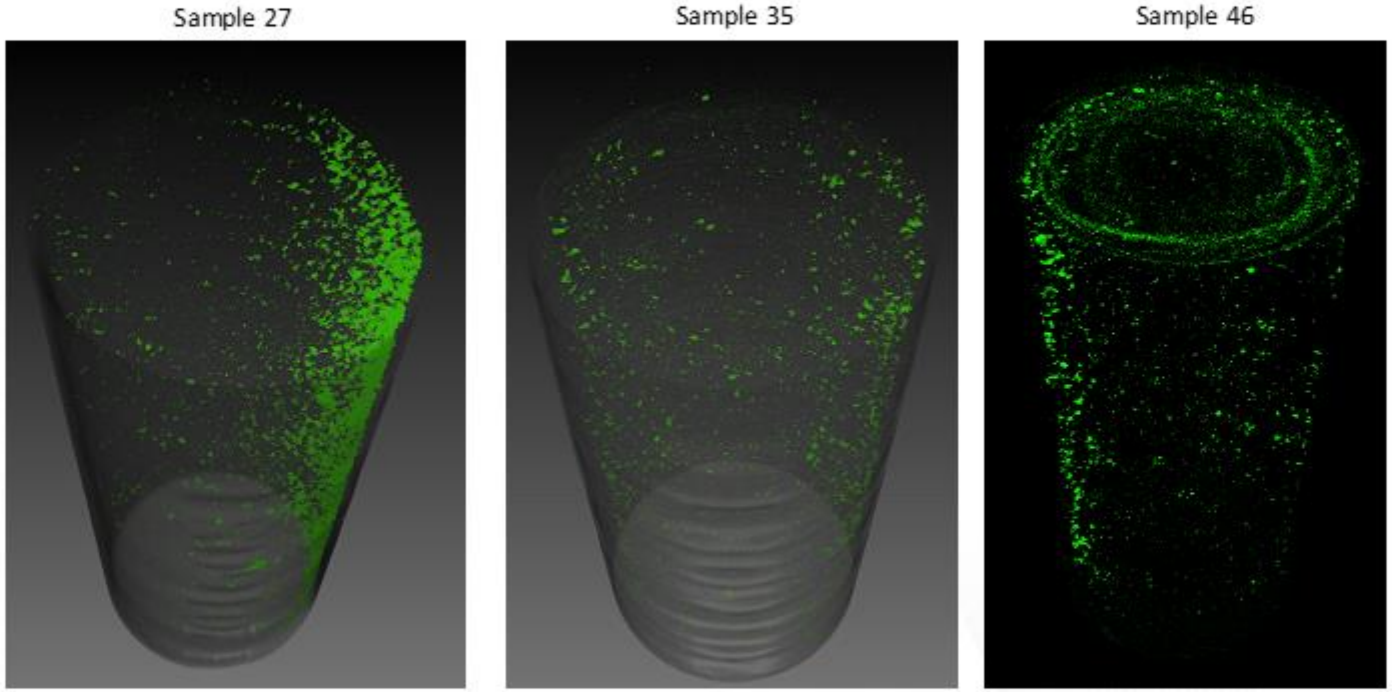


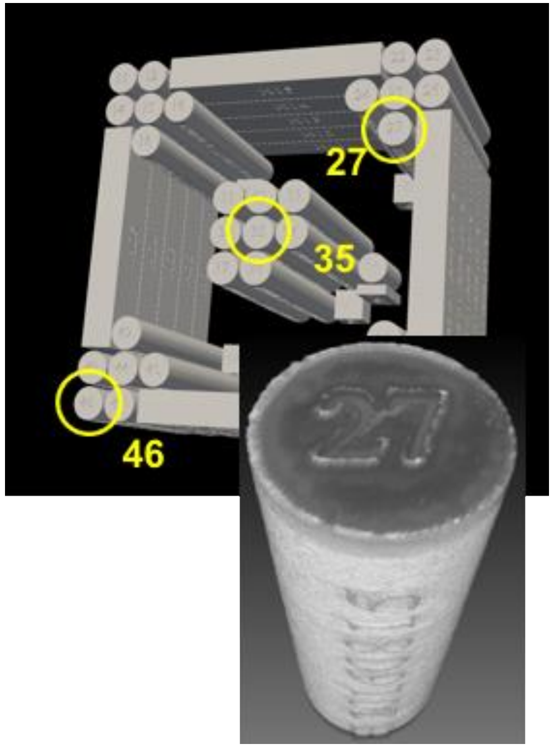
After HIP



Variations in AM – Build plate position

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

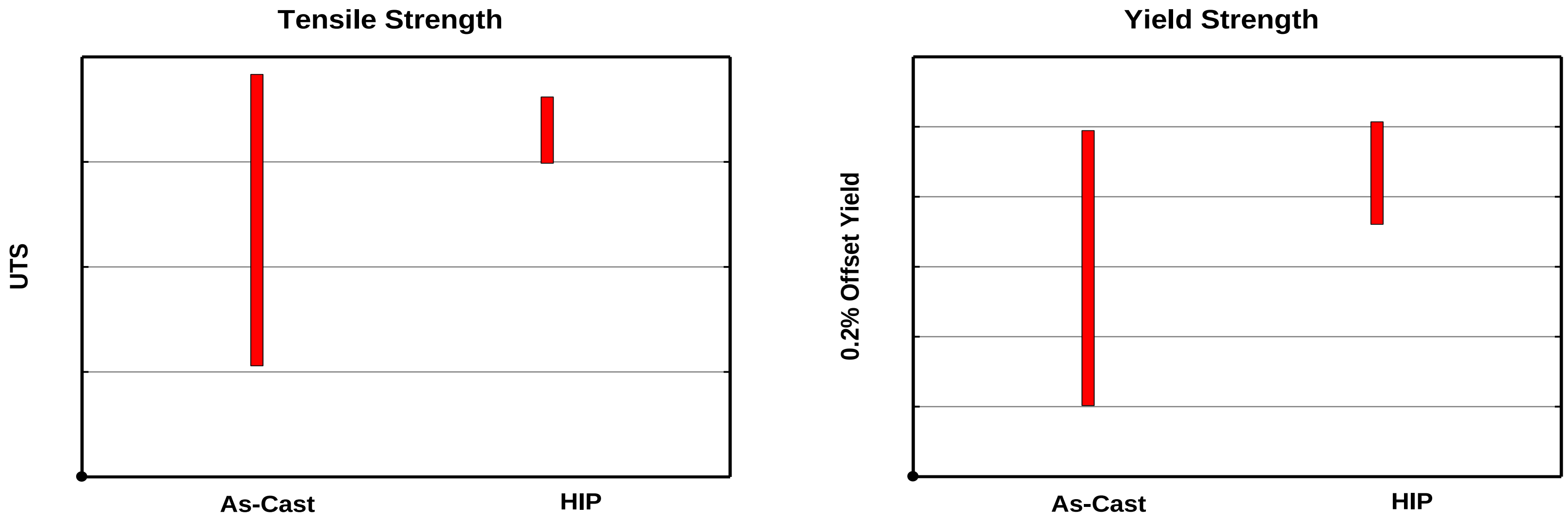




Courtessy of Oak Ridge National Lab

Typical effect on strength

Ultimate tensile and yield strength before and after HIP,
for typical nickel-base superalloys.

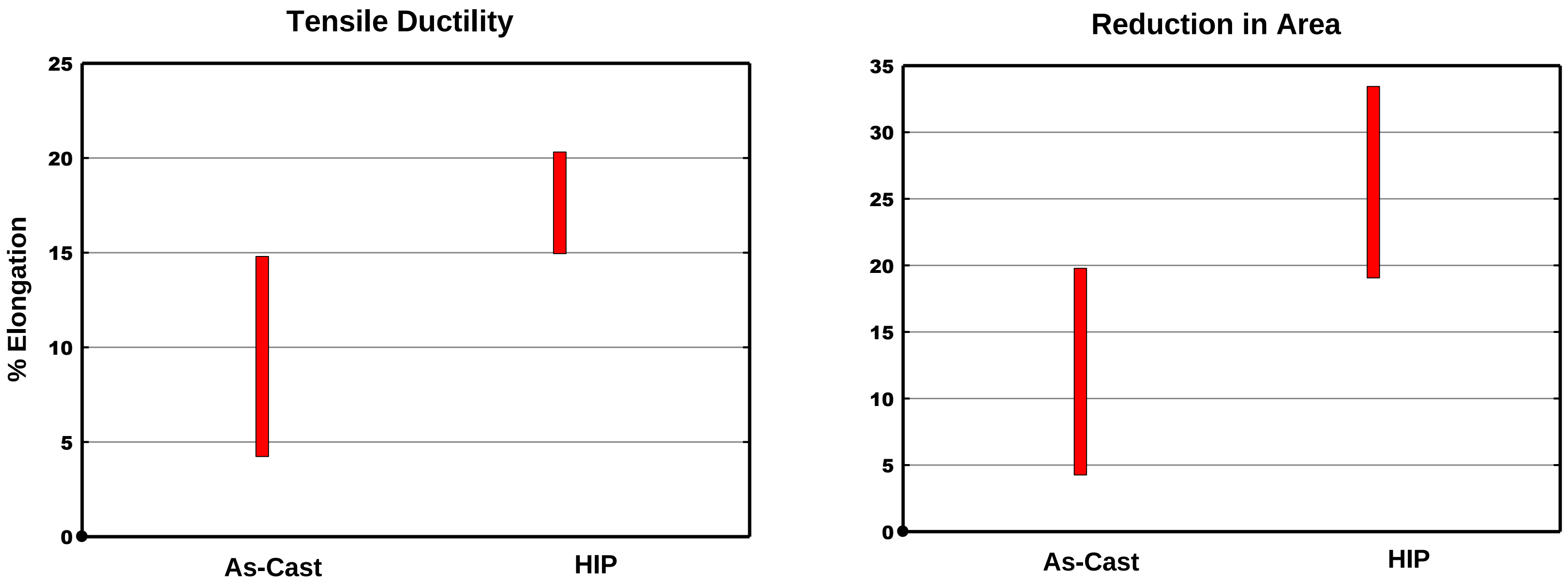


The scattering decreases 3 to 4-fold

Data courtesy of Howmet Corp.

Typical effect on ductility

Ductility before and after HIP, for typical nickel-base superalloys

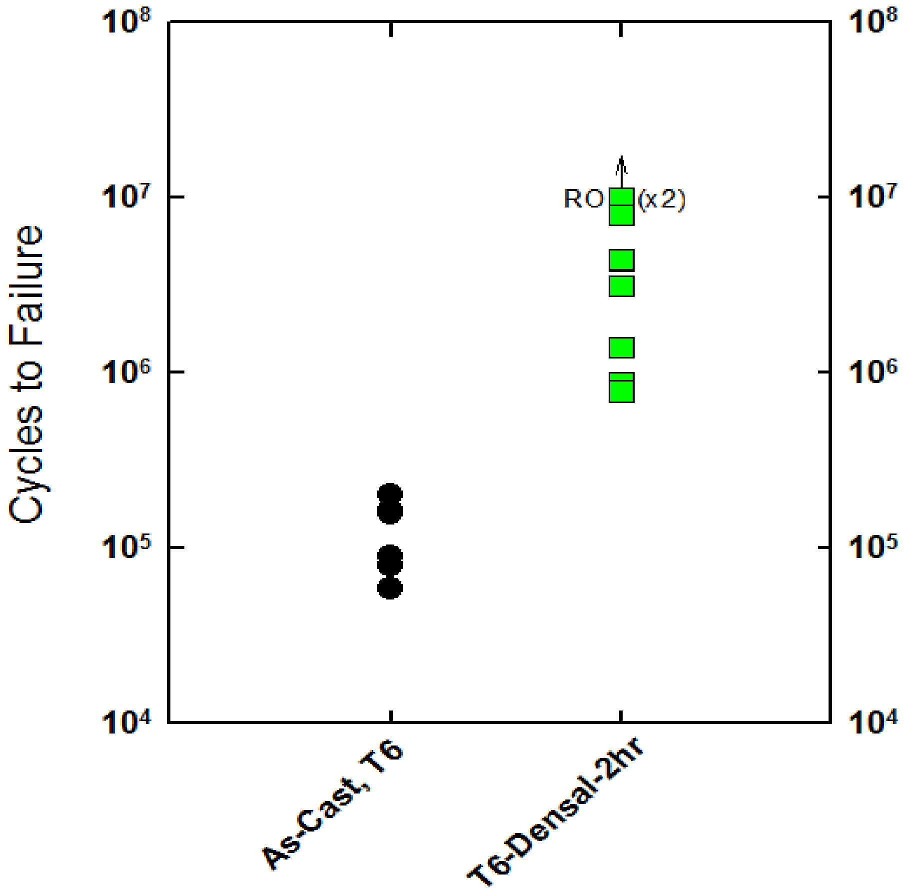


The minimum values increase 3 to 4-fold

Data courtesy of Howmet Corp.

Typical effect on fatigue

Fatigue life before and after HIP, for T6 Aluminum alloys

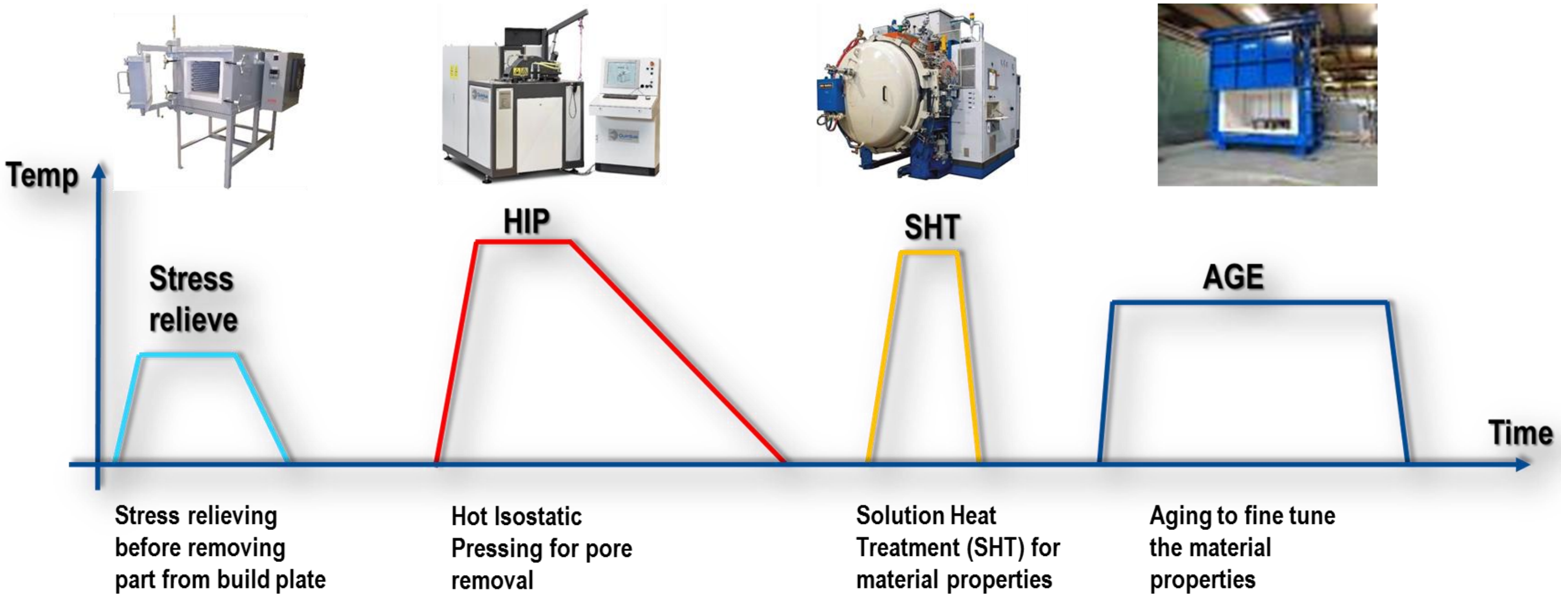


Fatigue life increases 10 to 100-fold

Data courtesy of Bodycote

High Pressure Heat Treatment

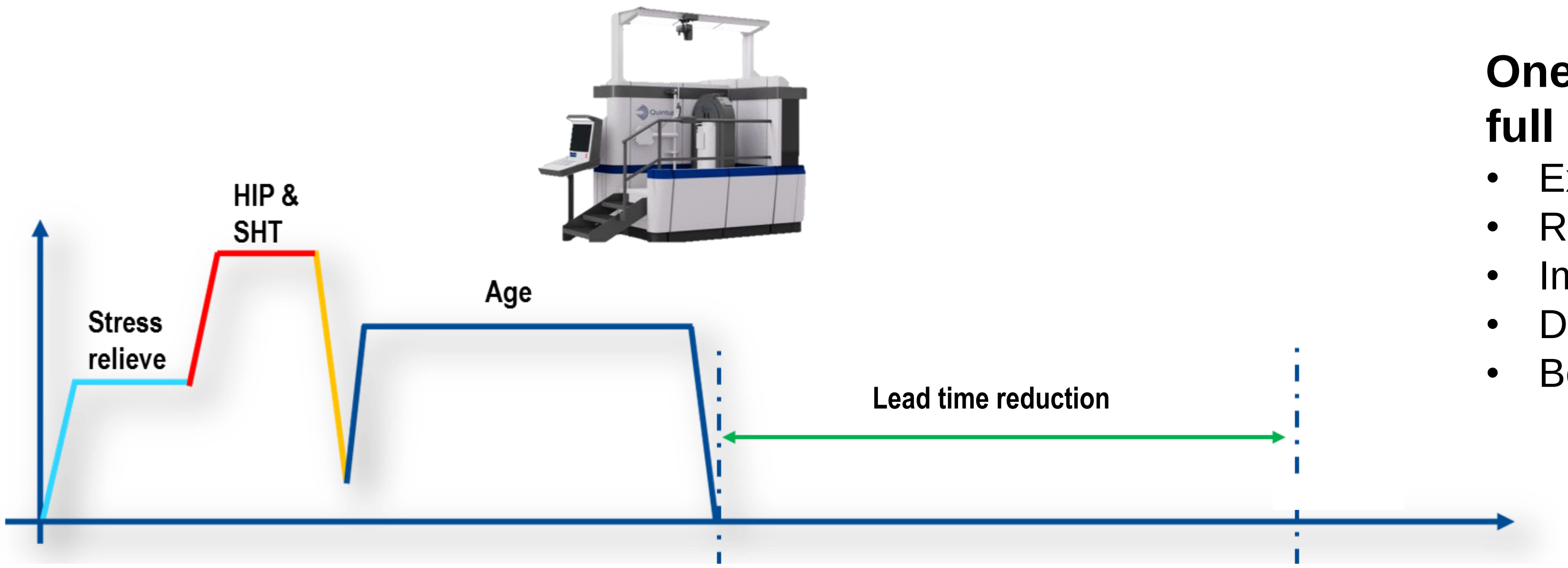
Conventional post process of an AM part



Conventional post process of AM

- Stress relieving for removal of part from build plate
- Hot Isostatic Pressing for defect elemination
- Solutionize and quench
- Aging/tempering for mechanical properties

High Pressure Heat Treatment of an AM part



One HIP system can take care of the full post process, which gives:

- Excellent process controll
- Reduced total process costs
- Improved Quality control
- Diminished downtime & leadtime
- Beneficial effects on the microstructure

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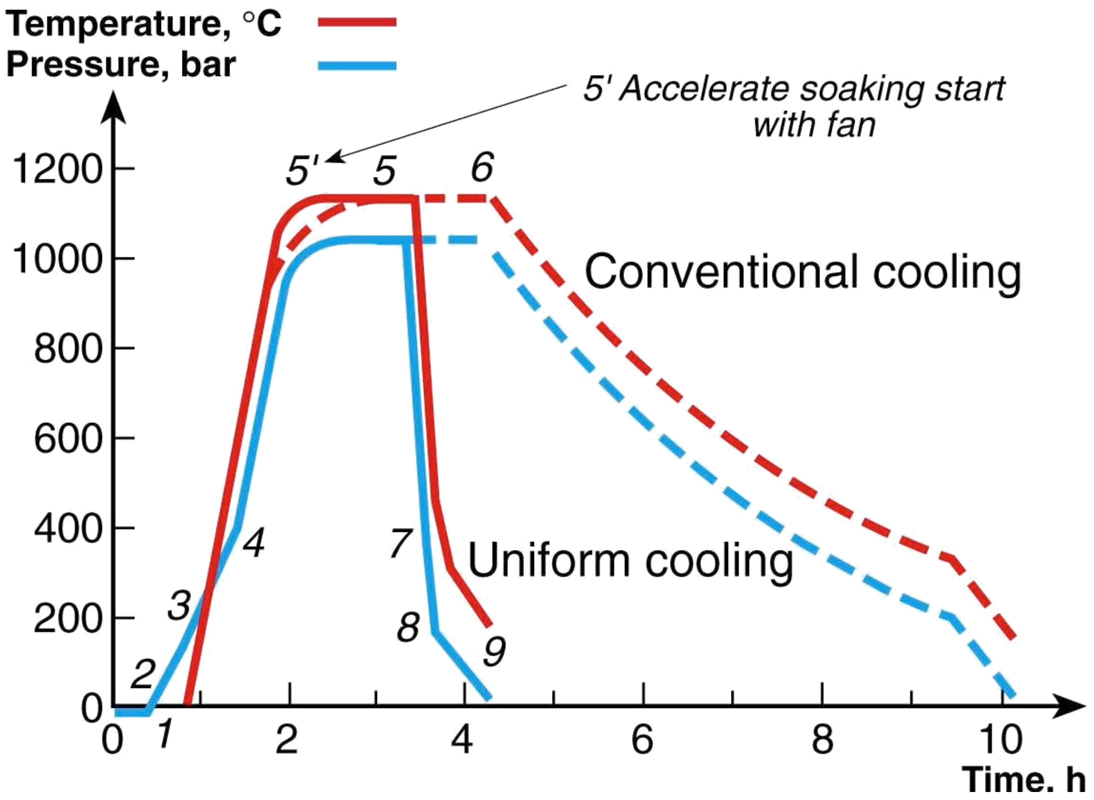
HIP System productivity - Uniform Rapid Cooling, URC®



1 Vacuum
2 Equalization
3 Pumping

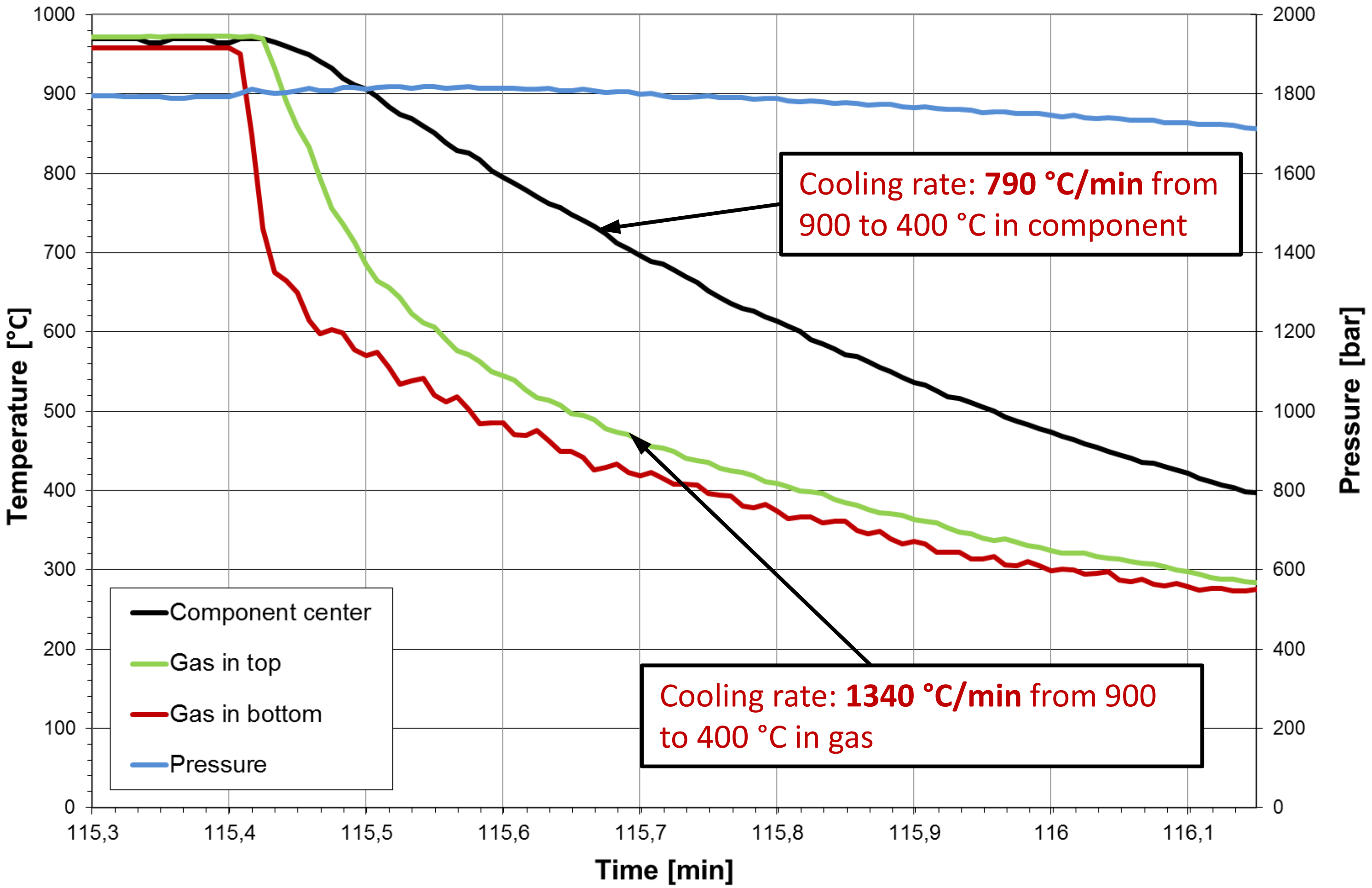
4 Heating
5 Holding
6 Cooling

7 Equalization
8 Back pumping
9 Release

Cooling rates: 150-500 °C/min

- URC® increases HIP productivity drastically
- With the URC® solution, high pressure heat treatment can be applied directly in the HIP
- With URC®, 50-100% faster cycle times can be achieved

HIP System productivity - Uniform Rapid Quenching, URQ®



Cooling rates: 500-3 500 °C/min

- URQ enables HIP quenching
- Heat treatment steps included in HIP cycle
- Physical properties in the material can be controlled

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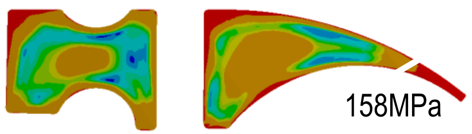
HIP System productivity - Uniform Rapid Quenching, URQ®

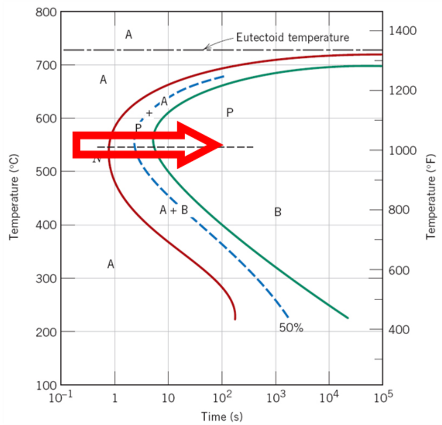
Benefits compared to conventional heat treatment

- Programmable temperature distribution
  - Excellent temperature accuracy during both heating and cooling
- Reduced thermal stresses
  - Low thermal gradient
  - No cracking
- No distortion of complex products or products with different material thickness
- The high pressure remains during quenching
  - Slower phase transformation kinetics in the Fe-C system
  - Delays perlite transformation ➔ lower cooling rate needed
  - Increased hardenability

Thermal stresses salt bath (60s)



Thermal stresses URQ (60s)



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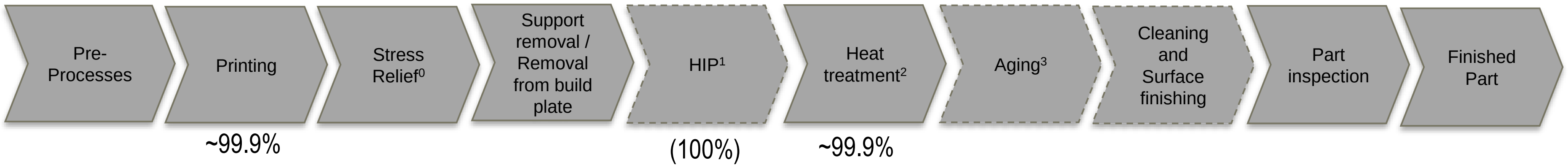
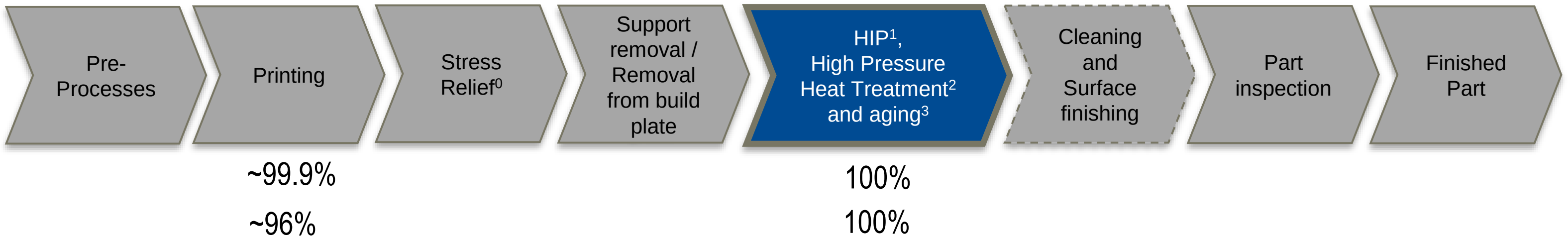
Increase productivity in the AM process flow

SLM



SLM



Traditional

High Speed

[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

Porous Printing and HPHT = Lean Additive Manufacturing™

Material and Build Set-Up → Printing, Stress Relief and Part Removal → HIP and Heat Treatment → Surface finishing → NDT and Inspection

L-PBF Ti6Al4V

Print Speed, V_s		Build time	Density
Standard	100%	24h 8min	99.3%
High Speed	167%	17h 15min	97.76%
Improvement	67%	26%	
Cost saving vs conventional production			>50%

Source: Herzog et al., MRS Spring Meeting 2019, April 22nd–26th, Phoenix

HIP cycle		Cycle time	UTS, MPa	Elong. %	Density
[2]Stress Relief	(no-HIP) 675°C, 2h, Furnace cool	2h	**1049±204**	**≈4%**	99.8%
[1,2]Standard	920°C, 100MPa, 2h, Furnace cool	8h	900±20	14.5%	99.99%
[2]Tailored #1	800°C, 200MPa, 2h, URC®	4h 48min	960±12	13.3%	100%
[2]Tailored #2	950°C, 170MPa, 2h, URQ® + (High Pressure Aging 540°C,1100 bar 4h)	5h 6 min (12h 15min)	**1030±10**	**11%**	100%

[1]Source: Industrial standard for Titanium ASTM B348, ASTM F3001
[2]Source: Ahlers et al., EuroPM Special Interest Seminar November 2019

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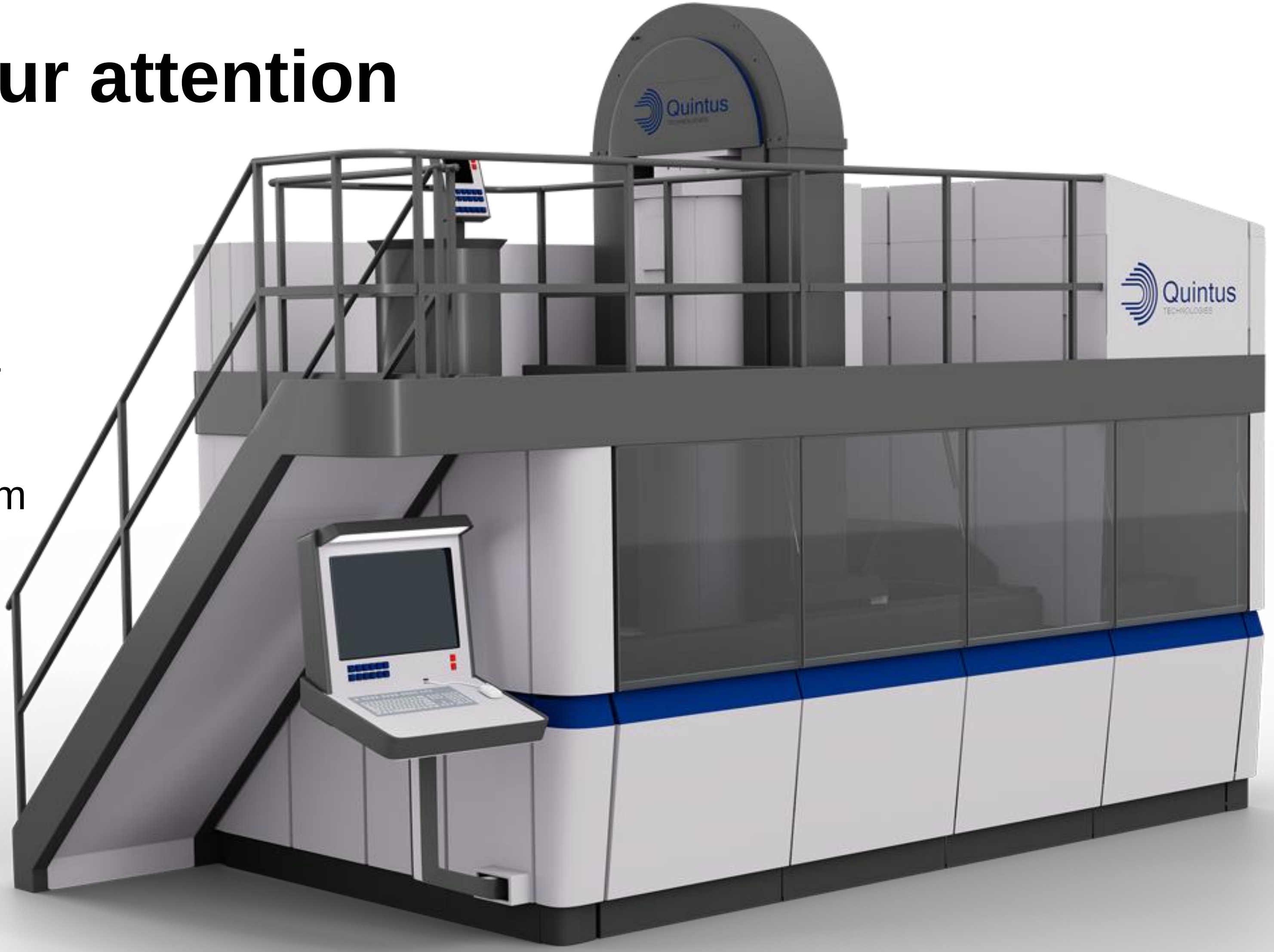
Conclusions

- HIP technology provides manufacturers with
  - Control of material properties.
  - Increased productivity with Uniform Rapid Cooling or Uniform Rapid Quenching
- Combining HIP and Heat Treatment
  - Shorter lead times
  - Higher productivity
  - Improved material properties
- Fatigue is greatly improved by HIP
  - EBM and SLM deposited powder gives same results after HIPing
- The yield strength can be increased by a simple optimization of the HIP parameters (pressure, temperature, time)
- Standards/specifications from the conventional manufacturing processes e.g. the casting industry might not be optimal for AM
- If the parts/material are to be HIPed the printing process can be adjusted for this
  - No need to print to >99.5 % density, i.e. print faster!
  - Printing with a larger line off-set also makes the printing process faster!
- With optimized printing parameters for HIP and optimized HIP parameters for AM, the highest strength can be achieved
  - Think HIP from the beginning!!

Thank you for your attention



Hans Södervall
Business Development Manager
Hot and Cold Isostatic Pressing
hans.sodervall@quintusteam.com