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

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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
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

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
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

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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)
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
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
Example: EBM AM 316L

- Powder bed fusion gives relatively high as-printed densities
  - HIP still have a large effect on the fatigue properties
Variations in AM – Build plate position

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

![Sample 27](image1)
![Sample 35](image2)
![Sample 46](image3)

Courtesy 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

Data courtesy of Bodycote

Fatigue life increases 10 to 100-fold
High Pressure Heat Treatment
Conventional post process of an AM part

- Stress relieving for removal of part from build plate
- Hot Isostatic Pressing for defect elimination
- 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 control
- Reduced total process costs
- Improved Quality control
- Diminished downtime & leadtime
- Beneficial effects on the microstructure
HIP System productivity - Uniform Rapid Cooling, URC®

- 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

Cooling rates: 150-500 °C/min

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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

Cooling rate: 790 °C/min from 900 to 400 °C in component

Cooling rate: 1340 °C/min from 900 to 400 °C in gas
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): 158MPa
- URQ (60s): 50MPa
Increase productivity in the AM process flow

1. Pre-processes
2. Printing
3. Stress Relief
4. Support removal / Removal from build plate
5. HiP¹
6. Heat treatment²
7. Aging³
8. Cleaning and Surface finishing
9. Part inspection
10. Finished Part

SLM

- Traditional
- High Speed

~99.9%
~96%
100%
100%
(100%)
~99.9%

¹ Removal of stresses created by printing process
² Removal of porosity and improvement of fatigue resistance
³ Adjustment of material properties
⁴ 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**

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### 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% | |

### HIP cycle

<table>
<thead>
<tr>
<th>Cycle time</th>
<th>UTS, MPa</th>
<th>Elong, %</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Relief</td>
<td>(no-HIP) 675°C, 2h, Furnace cool</td>
<td>2h</td>
<td>1049±20</td>
</tr>
<tr>
<td>Standard</td>
<td>920°C, 100MPa, 2h, Furnace cool</td>
<td>8h</td>
<td>900±20</td>
</tr>
<tr>
<td>Tailored #1</td>
<td>800°C, 200MPa, 2h, URC®</td>
<td>4h 48min</td>
<td>960±12</td>
</tr>
<tr>
<td>Tailored #2</td>
<td>950°C, 170MPa, 2h, URQ® + (High Pressure Aging 540°C, 1100 bar 4h)</td>
<td>5h 6 min (12h 15min)</td>
<td>1030±10</td>
</tr>
</tbody>
</table>

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1Source: Industry standard for Titanium ASTM B348, ASTM F3001
2Source: 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

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