The use of Modern HIP equipment for the investment castings industry

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HIP for the Castings Industry

Agenda

- Introduction to Hot Isostatic Pressing (HIP)
- High Pressure Heat Treatment (HPHT)
- Material property improvements with HIP
- Casting case studies involving HIP
- Summary

- Questions

Today’s speaker

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Introduction to Hot Isostatic Pressing (HIP)

Fundamentals, benefits, and equipment
HIP Fundamentals

HIP Definition:
“Applying an isostatic pressure, distinctly higher than the yield strength of the material at the HIP temperature”

Isostatic pressure?:
- Forming process that applies equal pressure in all directions on a product, compacting the workpiece uniformly from all sides
- Pressure must be applied with a fluid
- HIP: inert gas as pressure medium

Parameters:
- Temperatures are usually 500-2,000°C (932-3,632°F)
  - ~80% of materials solidus temperature
- Pressures are usually 100-200 MPa (15,000 to 30,000 psi)

Why?:
- Densification of Solids - elimination of internal defects
- Consolidation of Powder – densify encapsulated powder

Densification Mechanisms:
1. Mechanical deformation – internal defects begin to collapse
2. Creep
3. Diffusion bonding of the collapsed defect
Real Case Example: An Artificial Pore

Two cylinder halves, each with a drilled 1” diameter hole… are welded together to form one cylinder with a large void inside… The huge pore is eliminated by HIP!
Example: Metal Castings

Before HIP

After HIP

Defect Elimination Basics

- Only internal defects are eliminated
  - Surface connected porosity is not eliminated

- Gas tight surface required
  - Normally not an issue for castings

- Shrinkage corresponds to amount of densification
  - E.g. 1% porosity HIPed to 100% density ➔ 1% shrinkage by volume
  - 1% shrinkage by volume corresponds to 0.33 % linear shrinkage in each direction \((1 - \frac{3}{3})(1 - \text{voids removed})\)
HIP Cycle Parameters

- HIP temperature normally ~ 80% of material melting point ($T_{\text{solidus}}$)
  - Temperatures are usually 500-2,000°C (932-3,632°F)

- Pressure normally 7,000 - 30,000 psi (50 – 207 MPa)
  - Somewhat dependent on strength of material
  - Trend of increased HIP pressure for metal processing

- Normally between 1 - 4 hour soak time
  - High temperature creep alloys need longer HIP time
    - Superalloys, TiAl etc.

- Different parameter sets can give 100% density
  - The optimal parameter set can depend on other factors e.g:
    - Minimizing grain growth
    - Avoid or promote phase transformation
    - Process economy

HIP process window for TiAl
Benefit of HIPing

- Elimination of internal defects gives:
  - Elimination of stress concentrations and crack initiation points
- Superior material properties
  - Increased fatigue properties, 10 – 100x
  - Improved ductility and fracture toughness
  - Better creep properties
- Reduced property scatter
  - The natural variation in defects for a component is eliminated
  - More predictive properties
- Improved quality of machined/polished surfaces
  - Important for sealing applications
  - Improved corrosion, optical and esthetic properties
- Scrap rate reduction
- Strength is mainly determined by microstructure, not defects!
Important Considerations for Hot Isostatic Presses

- **Pressure vessel design**
  - Wire wounded pressure vessel
  - Pre-stressed thin walled forged cylinder
  - Integrated cooling circuits
  - Compressive stresses on the inner surface prevents crack initiation and growth
  - Leak before break criteria – critical crack length longer than cylinder wall

- **Productivity and System Flexibility**
  - Wire winding technology
  - Water cooled pressure vessel
  - Forced convection cooling
    Enables Rapid Cooling!
Rapid cooling HIP furnace technology

- Forced convection cooling
  - Gas circulation driven by fan and/or ejector
- Mixing of hot and cold gas
- The water cooled pressure vessel is used as heat exchanger
  - Additional heat exchanger inside pressure vessel for URQ
Typical parts of a HIP cycle

1. Vacuum
2. Equalization
3. Pumping
4. Heating
5. Holding
6. Cooling
7. Equalization
8. Back pumping
9. Release
High Pressure Heat Treatment (HPHT)
What is High Pressure Heat Treatment (HPHT)?

- Many HIP designs have slow cooling rates
  - Too slow for many types of heat treatment
  - Microstructure modification and optimisation must be done in further operation steps after HIP

- Modern Quintus® HIP systems can achieve high cooling rates
  - It is possible to perform in-situ heat treatment during the HIP cycle in the HIP system
  - Tailor-made microstructures and subsequent material properties are possible following defect elimination
Main purpose of High Pressure Heat Treatment

High Pressure Heat treatment gives:
- Reduced number of process steps
- Reduced total cycle time, down time & lead time
- Improved process and quality control
- Less time at elevated temperature

Savings in:
- Lead time
- Energy consumption
- Cost
- Capital investment
Min. 105 °F/min (58 °C/min) cooling rate needed after homogenization
- Purpose to avoid carbide formation
- 105 °F/min (58 °C/min) cooling is easily achieved in a modern HIP system

Typical post processing recommendations for CoCr

Heat treatment

The following heat treatment program is recommended.
1. Hot isostatic pressing (HIP) in a shared cycle, with the following parameters:
   - 1200 °C (2192 °F)
   - 1000 bar argon (14.5 ksi)
   - 240 minutes.
2. Homogenisation (HOM) heat treatment, with the following parameters:
   - 1220 °C (2228 °F)
   - 0.7–0.9 mbar argon (0.52 - 0.68 torr)
   - 240 minutes.

As rapid quench rate as possible, from 1220°C to 760°C in 8 minutes maximum. The purpose is to dissolve carbides and improve the isotropy of the microstructure, reducing the brittleness of the as-built EBM material.
Modern HIP System Flexibility

Mix between controlled cooling and rapid cooling

- Controlled cooling at 18 °F/min (9 °C/min)
- Rapid cooling start

Stop cooling/quenching at a predefined temperature

- Quench down to predefined temperature
Modern HIP System Flexibility

- Possible to add infinite many heating, soak, cooling, quenching steps etc. to the cycle
  - Tailormade heat treatment recipes
Benefits of HPHT

- The high pressure remains during cooling/quenching
- High pressure gas $\Rightarrow$ high density gas $\Rightarrow$ high thermal conductivity:
  - High heat transfer between the gas and components
- Continuous cooling of the medium from the same high temperature as the component
  - Low thermal gradients $\Rightarrow$ Low thermal stresses $\Rightarrow$ Low risk of cracks or distortion
- Performing the heat treatment under high pressure $\Rightarrow$
  - No risk of Thermally Induced Porosity (blistering)

Coupled FEM and CFD simulation of URQ quench and salt bath quench of a hammer head in 2D

Thermal stresses salt bath quench

- 158MPa

Thermal stresses URQ quench

- 50MPa
Optimized cooling results in repeatable material properties

Examples of materials with benefits of a specific cooling rate

- CoCr
- TiAl
- Duplex stainless steel
- Super duplex steel
- Tool steels
- Low alloyed steels
- Ni-base material
- Super alloys
- Ceramics
- Ausferrite Ductile Iron (ADI)
- Etc.

The effect of HIP cooling rate on CMSX-4
Latest High Pressure Heat Treatment product developments

**Quintus® QIH 60**
- **Hot Zone**
  - Diameter: 410mm (16.14 inch)
  - Height: 1000mm (39.37 inch)
  - Working pressure: 400 to 2,070 bar (5,800 to 30,000 psi)
  - Max Temperature: 2,000°C (3,632°F)
  - Cooling rate: >500°C/min

**Quintus® QIH 122**
- **Hot Zone**
  - Diameter: 660mm (25.98 inch)
  - Height: 1750mm (68.9 inch)
  - Working pressure: 400 to 2,070 bar (5,800 to 30,000 psi)
  - Max Temperature: 2,000°C (3,632°F)
  - Cooling rate: >200°C/min

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Application Center

- In-house application R&D
- Evaluation of new HIP processes/applications
- Optimization of current HIP processes
- Proof of concept for potential customers
- Training and education on the equipment for new customers
- Gain knowledge about equipment in operation over time

R&D collaborations with the most prominent universities, institutes and companies globally
Material property improvements with HIP
Design advantages from reduced scatter

Nickel base super alloy castings

- Scatter in strength values reduced 3-4 fold
- Minimum strength values increased significantly
- Ductility values increased significantly

➢ Using HIP can improve design parameters significantly whilst facilitating repeatable production

Data courtesy of Howmet Corp.
HIP lifts the fatigue resistance of cast parts as well as AM

HIP of Cast Material

- Significantly increased fatigue resistance
- Closed porosity
- Mechanical properties approaching those of forged material based on tailored HIP cycles and/or HPHT cycles

Example: Typical Effect on Fatigue Life

- **Cast Al alloy A206**
  - T71 heat treated
  - With and without HIP
  - 10 specimens per condition
  - 1 stress level: 24 ksi (170 Mpa)

- **HIP improves fatigue life**
  - Over 30 times higher minimum value
  - Over 90 times higher average value

Casting Case Studies involving HIP
Main HIP applications

Densification of Products
Improve quality for castings, additive manufacturing, and sintered materials

Consolidation of Powder
Near-Net-Shape components or billets of stainless steels, tool steels, HSS

Diffusion Bonding
To join similar or dissimilar materials together in the solid state. Solid to solid, Powder to solid or powder to powder

High Pressure Heat Treatment
To combine HIP and Heat Treatment cycles to improve product properties and reduce lead time

Courtesy of MTC Japan

Courtesy of Bodycote
AM Sand Mould Casting Applications

Mitigation of porosity issues

- Design of moulds with filling channels, gate and cooling system to achieve an even cooling rate with minimal shrinkage
- Design of mould to move the last solidification zone outside of the main part
- 3D printing of moulds with short delivery times and repeatability
- Aluminum, magnesium, iron, steel, etc.

Hot Isostatic Pressing

- Defect healing – reduced weld repair
- Properties close to those of forgings
- Complex Near Net Shape parts with short delivery times and uniform properties
- Reduced overall costs
Porosity – a natural result of solidification

Material solidifies from the outside in

Solidification causes porosity

- Shrinkage porosity
  - Material shrinkage during solidification
- Gas porosity
  - Decreased gas solubility during cooling

➢ Internal defects in the as-cast condition

- Internal defects
  - Stress concentrations
  - Crack initiation points
  - Corrosion initiation points
  - Negative influence on material properties
  - Give rise to NDT and weld repair (where allowed)
The use of HIP to improve machined surfaces

Defects are closed prior to machining

- Subsequent machining does not open new porosity
  - This is especially of interest in corrosion environments
  - Flange and seal surfaces are of particular interest
  - Segregations in Forgings can have similar issues

HIP helps avoid substantial costs for weld repair

Design and fabrication of a 1m titanium sphere for 4000m ocean depth. D Pargett
Conference: IEEE Oceans - San Diego, 2013

Courtesy Midland Impregnations
Main HIP applications

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*Courtesy of MTC Japan*

*Courtesy of Bodycote*
HPHT Example: Ni-base Cast Single Crystal

- Study by Ruhr-Universität Bochum, Germany, on second generation single crystal ERBO/1 (a variation of CMSX-4)
  
<table>
<thead>
<tr>
<th>Co</th>
<th>Al</th>
<th>Cr</th>
<th>Mo</th>
<th>Ti</th>
<th>Ta</th>
<th>Re</th>
<th>W</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.7</td>
<td>5.6</td>
<td>6.4</td>
<td>0.6</td>
<td>1.0</td>
<td>6.5</td>
<td>3.0</td>
<td>6.4</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

- Variants studied:
  - Heat treated (HT) material
  - HIP + HT material (HPHT combined in HIP)
- Density, microstructure and high/low temp creep evaluated

Test matrix

<table>
<thead>
<tr>
<th>Variant #</th>
<th>Label</th>
<th>Process Condition</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HT</td>
<td>SA 2372 F (1300°C) 6h ➔ Cooling to RT ➔ Ageing at 2084 F (1140°C) 4h + 1600 F (870°C) 16h</td>
<td>~150 °C/min (270 °F/min)</td>
</tr>
<tr>
<td>2</td>
<td>HPHT</td>
<td>Same treatment but integrated in the HIP @15000 psi (100 MPa)</td>
<td>~ 1500 °C/min (2700 °F/min)</td>
</tr>
</tbody>
</table>

Ni-base Cast Single Crystal

HT Variant #1: Conventional processing

- Requires 3 main steps

Casting
Homogenization
Precipitation Hardening


HT Variant #2: Modern HPHT processing

- Integrated into single step under pressure

Casting
- Bridgeman technique to acquire SX structure
- Undesired microstructure/segregation due to slow cooling
- Formation of large cast pores

Homogenization
- Reduce segregation
- Step wise function with long holding time to avoid incipient melting
- 10-12 hrs for ERBO/1
- New porosity is further developed at inter-dendritic regions
- During cooling gamma prime forms but not with ideal shape or size

Precipitation Hardening
- Performed in 2 steps to optimize the gamma/gamma prime microstructure
Ni-base Cast Single Crystal

**HT Variant #1: Conventional processing**
- Requires 3 main steps

**HT Variant #2: Modern HPHT processing**
- Integrated into single step under pressure

**Microstructural Evolution**
- Dendritic in nature
- Eutectic regions still present
- Porosity present:
  - As-cast - irregular shape
  - Homogenization – round shape
- Developed gamma/gamma structure

Ni-base Cast Single Crystal

HT Variant #1: Conventional processing
- Requires 3 main steps

HT Variant #2: Modern HPHT processing
- Integrated into single step under pressure

Ni-base Cast Single Crystal

HT Variant #1: Conventional processing

- Requires 3 main steps

HT Variant #2: Modern HPHT processing

- Integrated Homogenization + HIP

Optimized properties using high speed cooling under pressure

- The porosity remains in the conventionally heat treated material
- The cast porosity is eliminated by the HIP+HT cycle

Conventional HT = 0.244 area % porosity

Combined HPHT = 0.002 area % porosity

ERBO/1 Variants

- Same γ'-volume fraction for both variants ~ 75 %
- Finer γ/γ'- microstructure for combined HIP and HT
  - Due to the faster cooling in HIP after solution annealing

The effect of HIP and HPHT on creep properties of Ni-base SX

- Longer creep life for HIP:ed material for both low and high temperature creep
  - Due to reduction in amount and size of cast porosity with HIP

- HIP gives lower minimum creep rate for low temperature creep
  - Probably due to the finer γ/γ'- microstructure achieved by HIP due to the higher cooling rate

Rejuvenation of turbine blades is commonly conducted using HIP

- Superalloy turbine blades are subjected to high temperatures and stresses during operation in flying and stationary gas turbines
- These demanding operations conditions leads to microstructural changes in the blade:
  - Formation of internal pores
  - Break-up of the $\gamma/\gamma'$-microstructure
  - Increased dislocation density
- These changes in the blade during operation impair the properties of the blade and will eventually lead to rupture
- With a combined HIP+HT the properties of the damaged blade can be restored to the same levels as a new blade
- Evaluation performed on second generation single crystal ERBO/1 (a variation of CMSX-4)
A combined HIP+HT process can be used to close internal porosity, restore microstructure and decrease dislocation density at the same time.

Recrystallization of the single-crystal blade is avoided by using the correct rejuvenation temperatures.

![Graph showing HIP+HT rejuvenation process](image)
Elimination of creep induced internal porosity

Porosity Evolution:
- The HIP step eliminates the creep induced porosity and the porosity from the fabrication of the new blade

Microstructure before operation (Not HIP:ed)
- 0.3 % porosity

Microstructure after operation
- 0.64 % porosity

Microstructure after operation and after HIP+HT rejuvenation
- 0.08 % porosity

Ref: Rejuvenation of creep resistance of a Ni-base single-crystal superalloy by hot isostatic pressing, B. Ruttert et al, Material & Design Volume 134, 15 November 2017, Pages 418-425

The porosity level in the used and rejuvenated blade is even lower than in the new unused blade
Restoration of $\gamma/\gamma'$-microstructure

Microstructural Evolution:
- The $\gamma/\gamma'$-microstructure changes during operation, decreasing the creep resistance of the material
- The HIP+HT process restores the microstructure completely to its initial state

Ref: Rejuvenation of creep resistance of a Ni-base single-crystal superalloy by hot isostatic pressing, B. Rutter et al, Material & Design Volume 134, 15 November 2017, Pages 418-425
HIP+HT rejuvenation conclusions

- A combined HIP+HT rejuvenation process can restore creep degraded Ni-base single-crystal superalloy material to its initial state
  - Restore the gamma/gamma prime microstructure
  - Performed without any recrystallization
  - Close creep induced porosity
  - Regain creep properties
- The rejuvenation process is a very attractive alternative to buying new blades
Summary

Densification of Products
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Thank you for your attention!

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