The use of Modern HIP equipment for the investment castings industry

Chad Beamer
Applications Engineer
Quintus Technologies, LLC

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

Chad Beamer
Applications Engineer - AMD
chad.beamer@quintusteam.com
Tel : 614 404 3982

Introduction to Hot Isostatic Pressing (HIP)

Fundamentals, benefits, and equipment

Quintus TECHNOLOGIES

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 500-2,000ºC (932-3,632ºF)
  - ~80% of materials solidus temperature
- Pressures are usually 100-200 MPa (15,000 to 30,000 psi)

Why?:

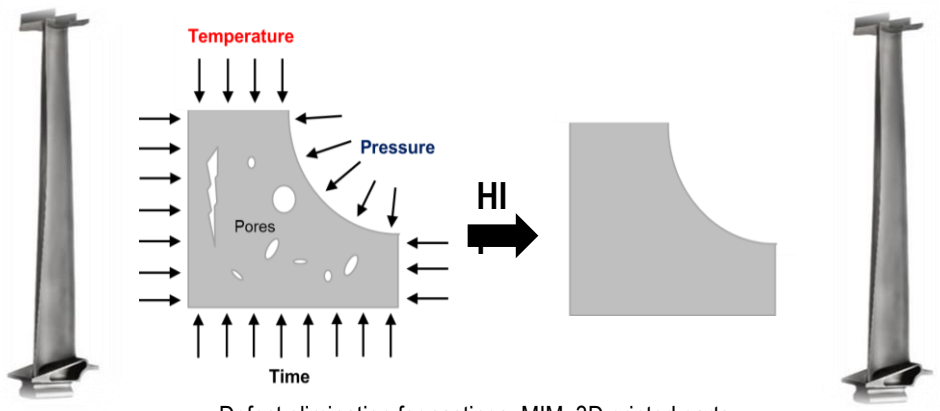
- Densification of Solids - elimination of internal defects
- Consolidation of Powder – densify encapsulated powder

Densification Mechanisms:

1. Mechanical deformation – internal defects begin to collapse
2. Creep
3. Diffusion

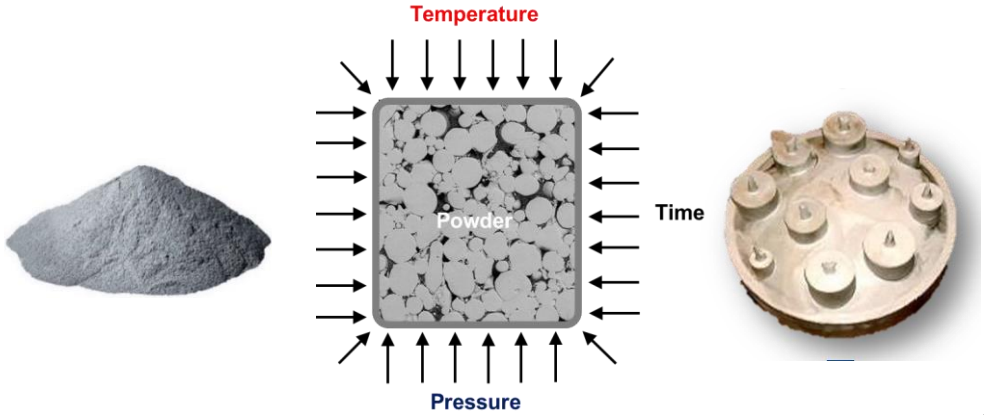
bonding of the collapsed defect

Densification of Solids



Defect elimination for castings, MIM, 3D printed parts

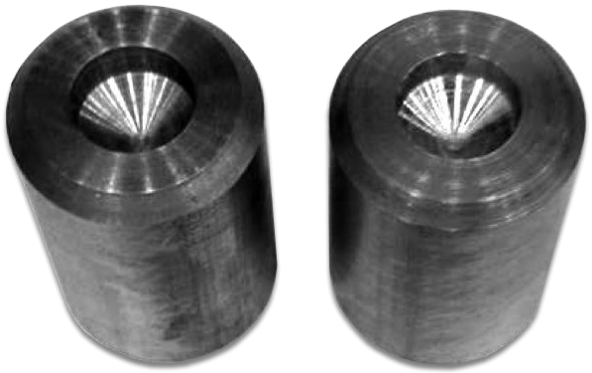
Consolidation of Powder



PM HIP – Powder billet or NNS components

Quintus TECHNOLOGIES

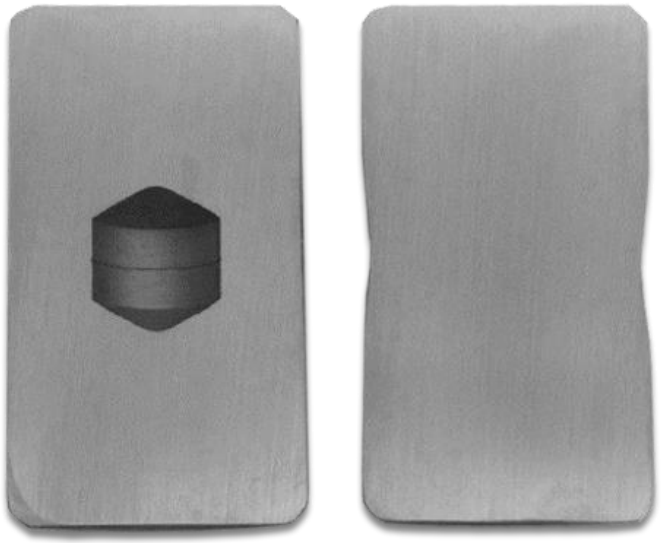
Real Case Example: An Artificial Pore



Two cylinder halves, each with a drilled 1” diameter hole…

are welded together to form one cylinder with a large void inside…

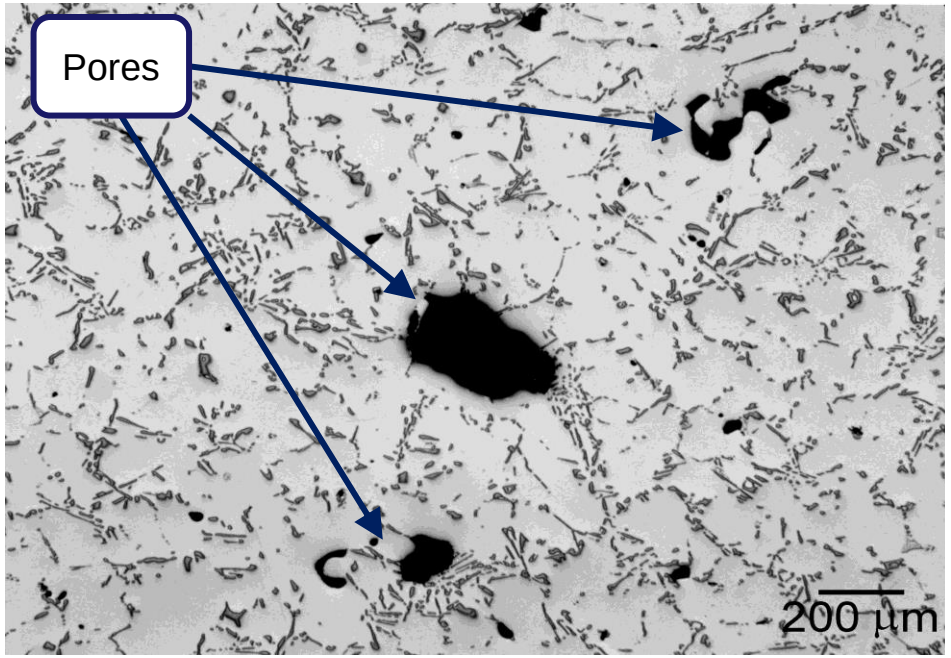
Before HIP **After HIP**



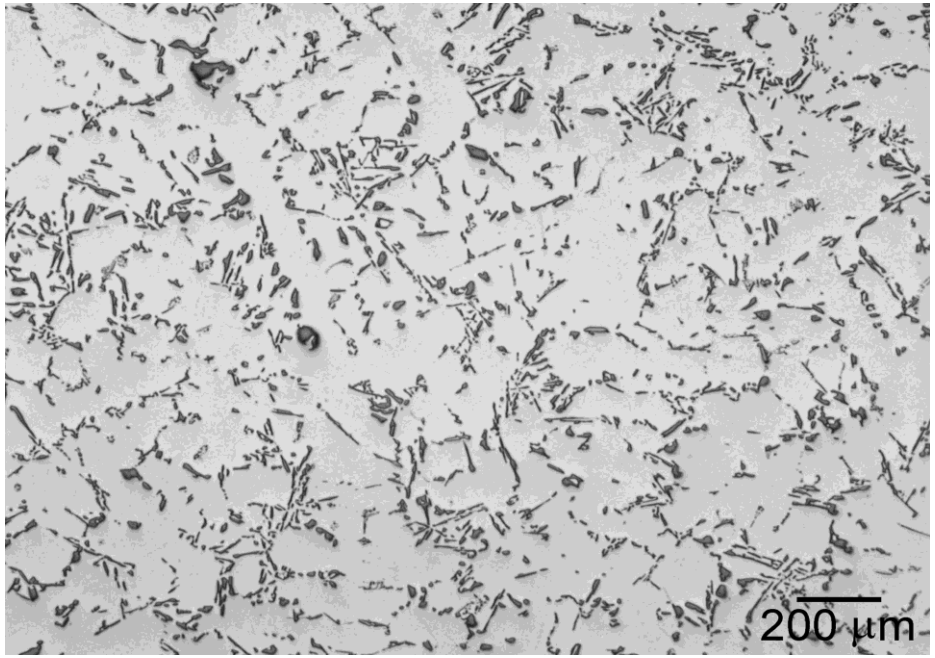
The huge pore is eliminated by HIP!

Example: Metal Castings

Before HIP



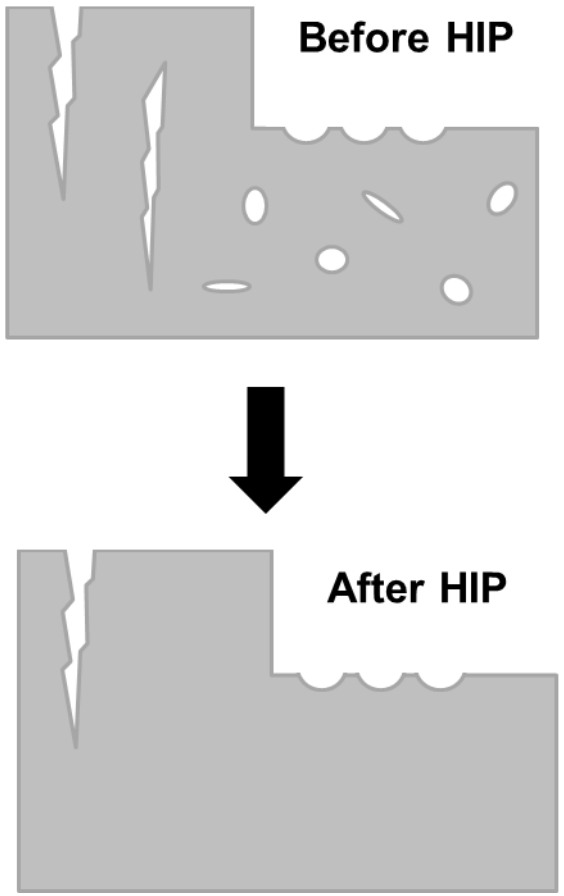
After HIP



Ref: S. Mashl et al., *Hot Isostatic Pressing of A356 and 380/383 Aluminum Alloys: An Evaluation of Porosity, Fatigue Properties and Processing Costs,* SAE 2000 world congress, 2000, Detroit, MI

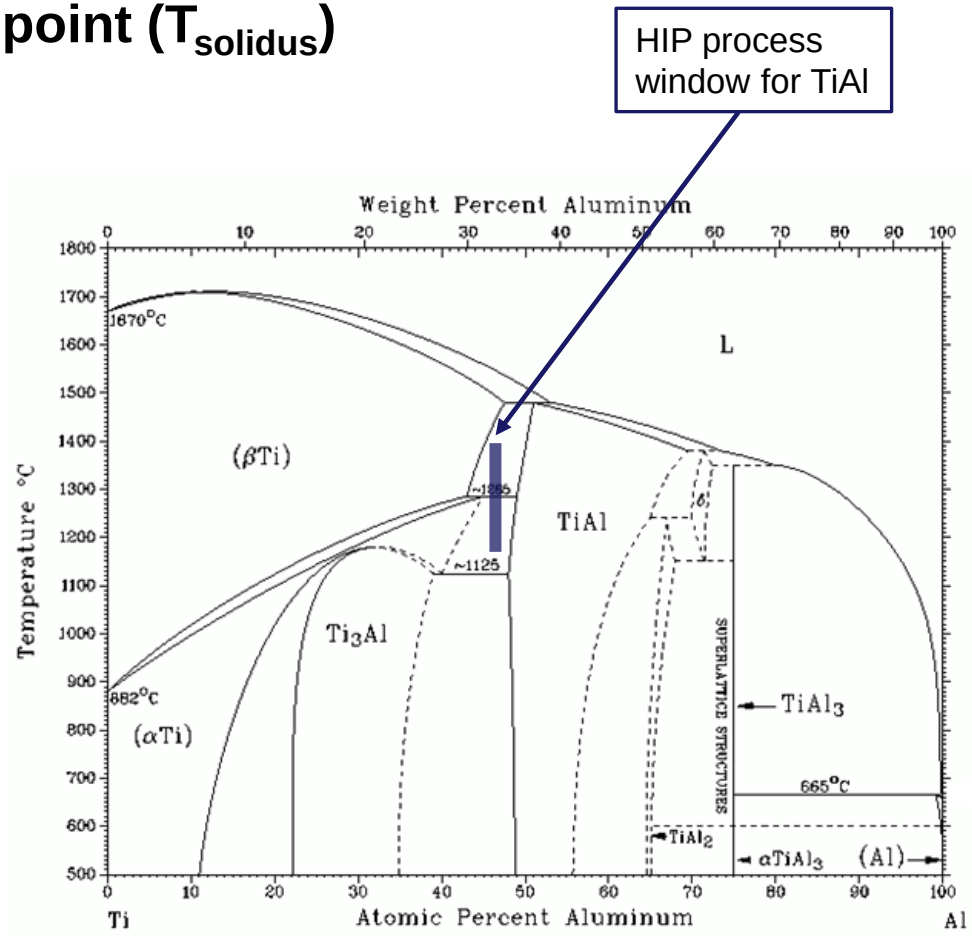
Defect Elimination Basics

- **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− $\sqrt[3]{(1-\text{voids removed})}$)**



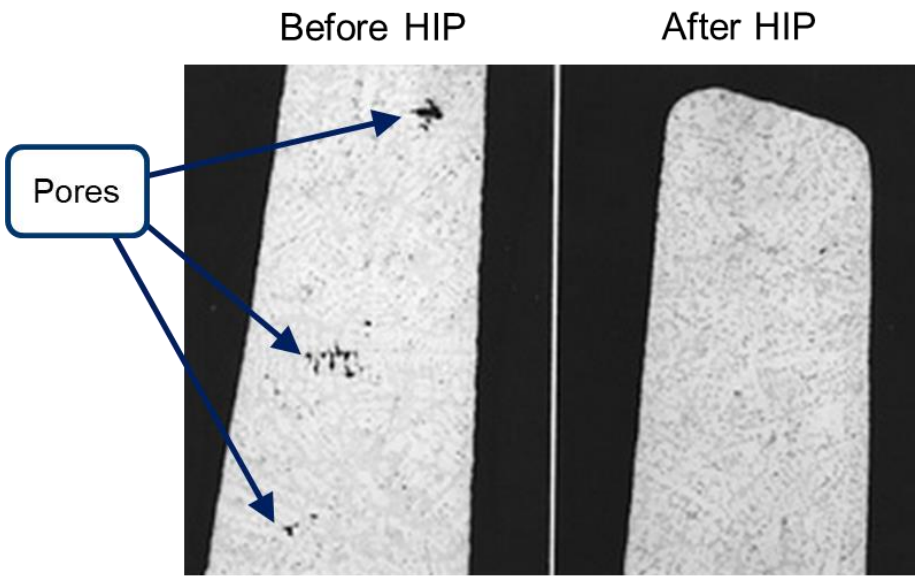
HIP Cycle Parameters

- **HIP temperature normally ~ 80% of material melting point ($T_{solidus}$)**
  - **Temperatures are usually 500-2,000ºC (932-3,632ºF)**
- **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**

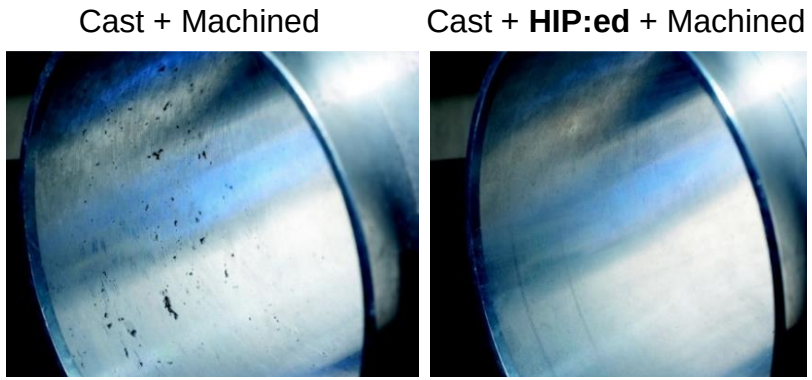


Benefit of HIPing

- **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!**



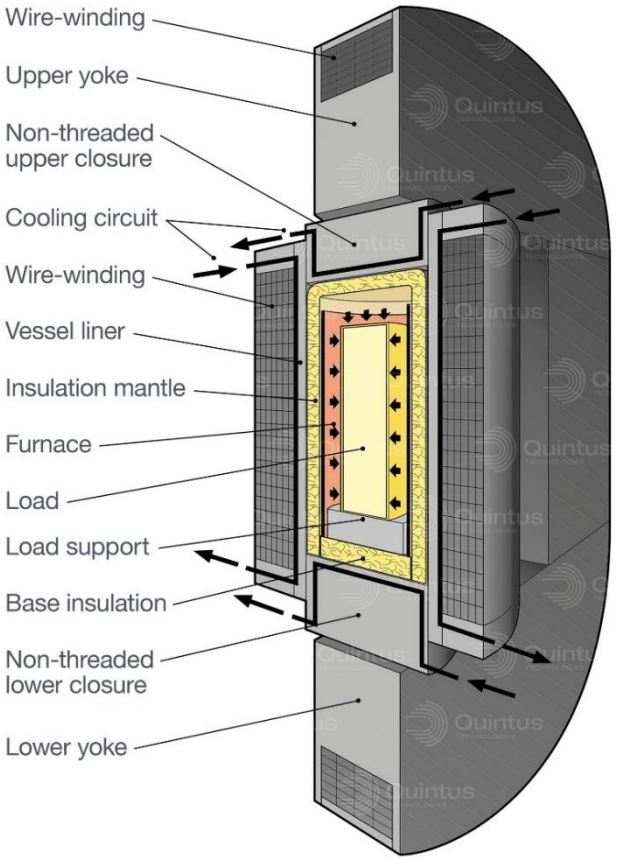
Source: Bodycote

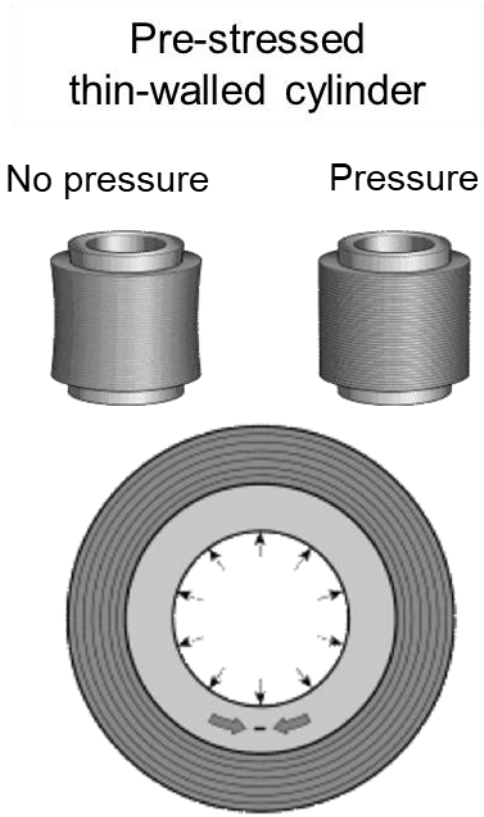


Important Considerations for Hot Isostatic Presses

- **Pressure vessel design**
  - **Wire winded 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**

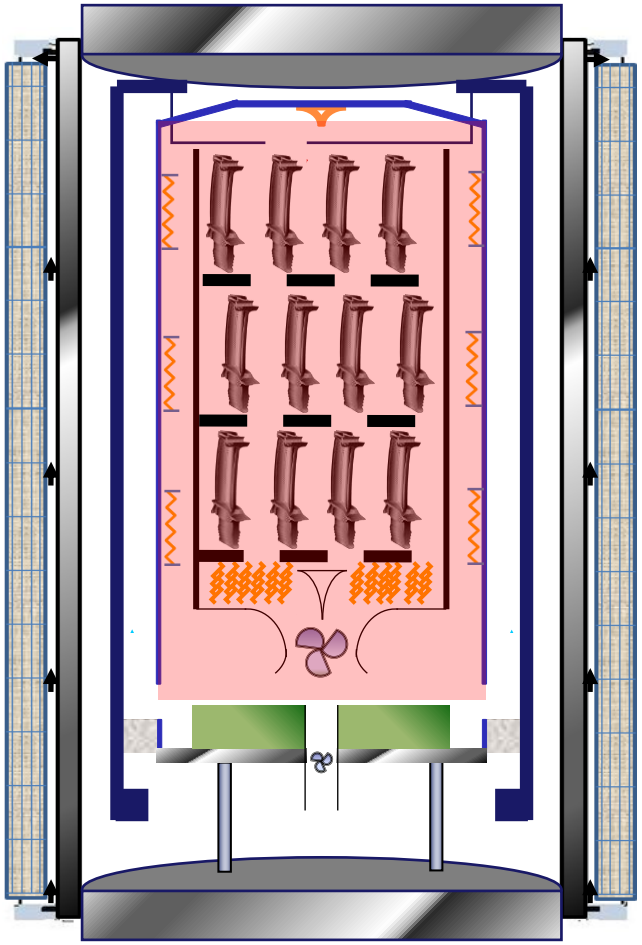
Enables Rapid Cooling!





Rapid cooling HIP furnace technology

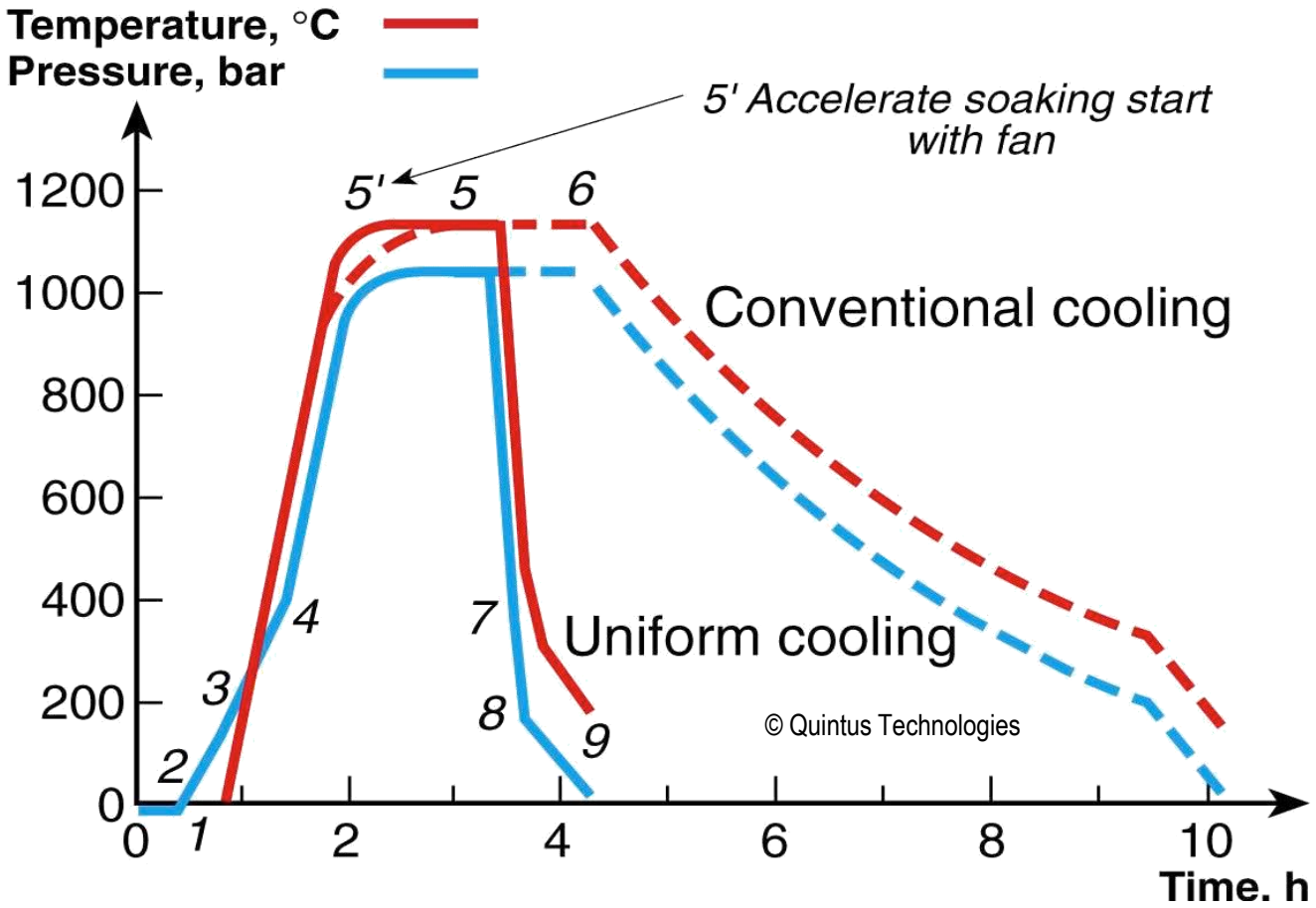
- Forced convection cooling
  - Gas circulation driven by fan and/or ejector
- Mixing of hot and cold gas
- The water cooled pressure vessel is used as heat exchanger
  - Additional heat exchanger inside pressure vessel for URQ



Quintus TECHNOLOGIES

Typical parts of a HIP cycle

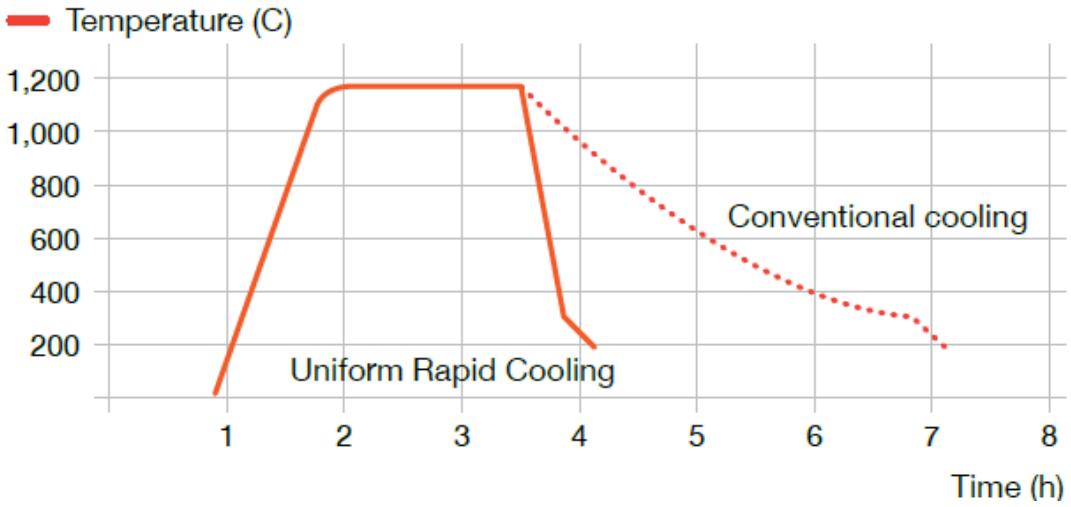
1. Vacuum
2. Equalization
3. Pumping
4. Heating
5. Holding
6. Cooling
7. Equalization
8. Back pumping
9. Release



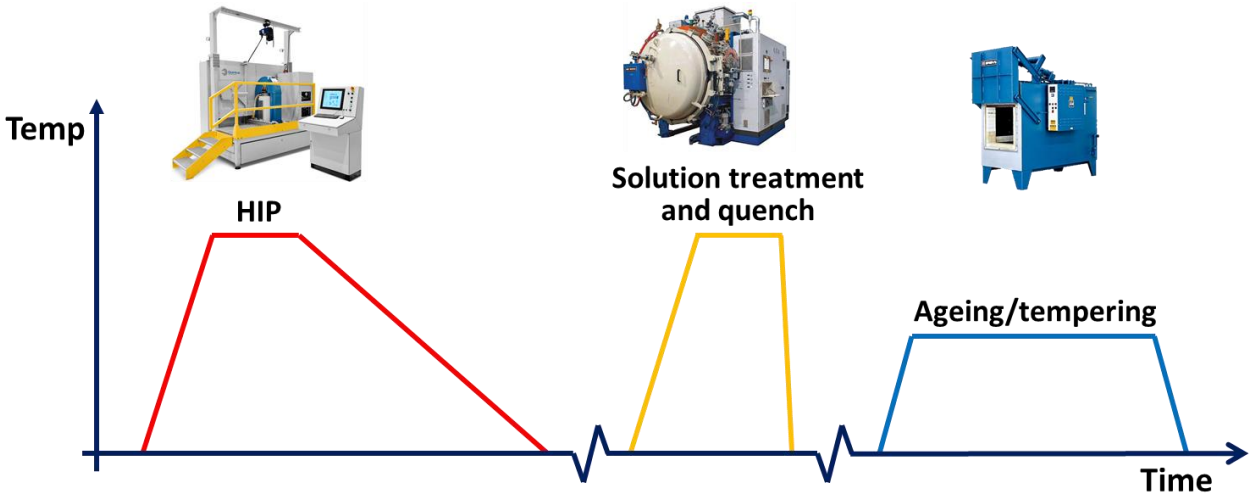
High Pressure Heat Treatment (HPHT)

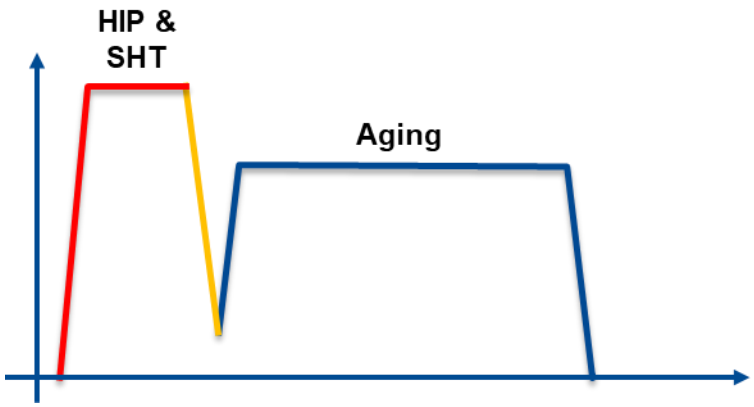
What is High Pressure Heat Treatment (HPHT)?

- **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

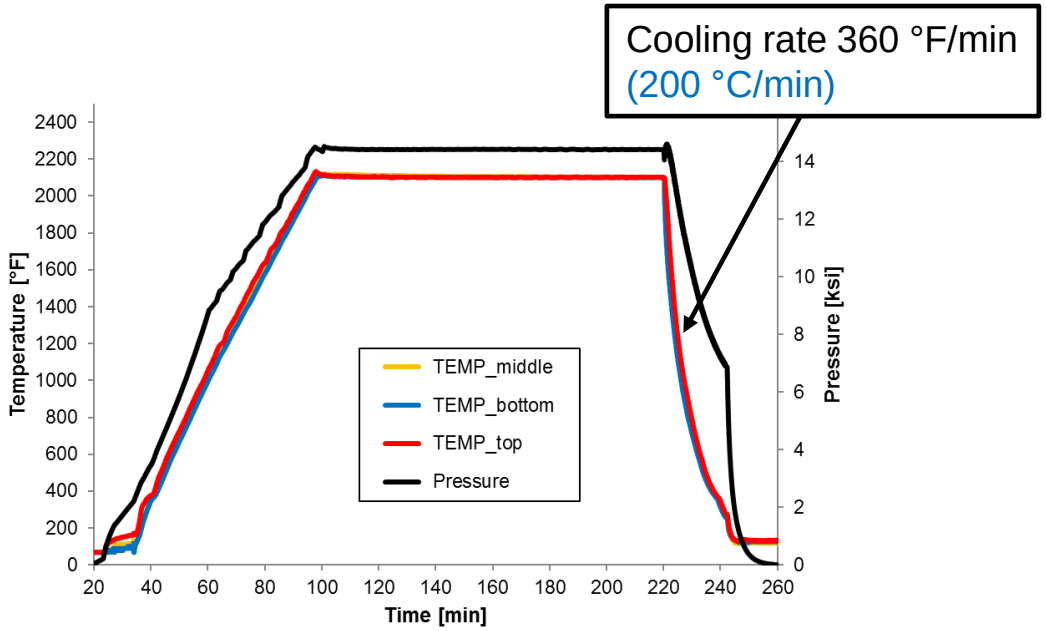
Savings in:

- Lead time
- Energy consumption
- Cost
- Capital investment

Quintus TECHNOLOGIES

Example: CoCr ASTM F75

- 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

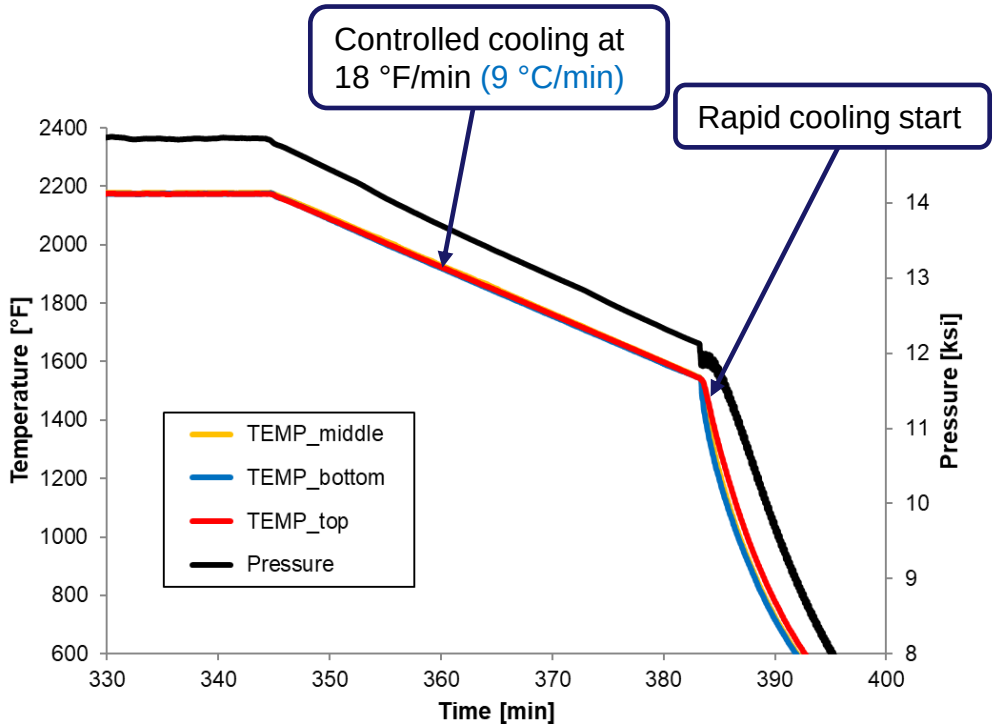
The following heat treatment program is recommended.

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. (2228 °F) (1400 °F)

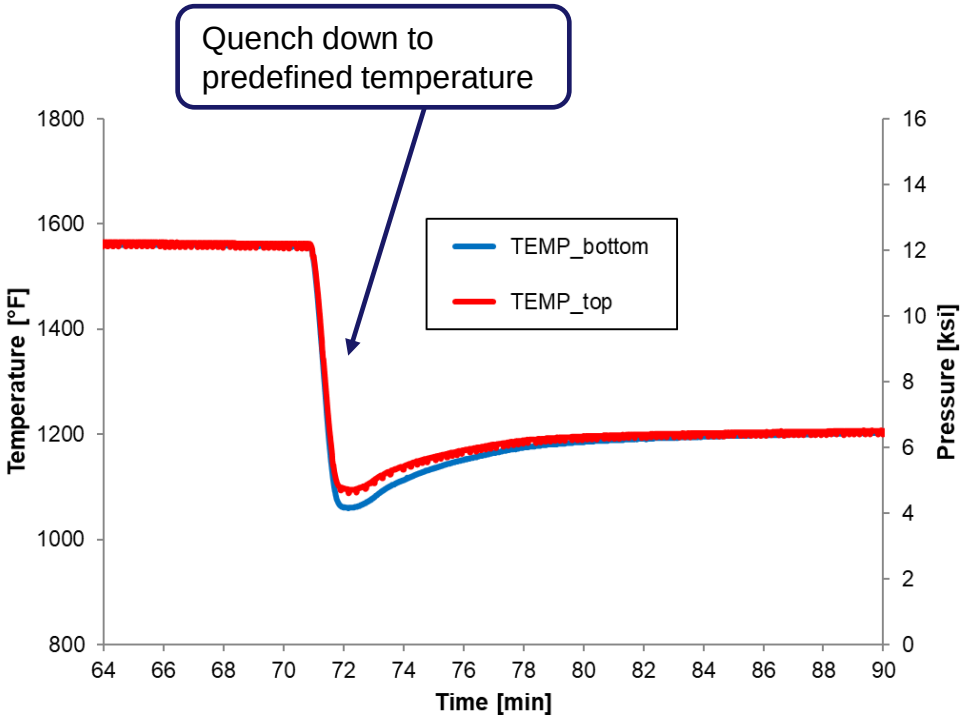
As rapid quench rate as possible, from 1220°C to 760°C in 8 minutes maximum. The purpose is to dissolve carbides and improve the isotropy of the microstructure, reducing the brittleness of the as-built EBM material.

Modern HIP System Flexibility

Mix between controlled cooling and rapid cooling

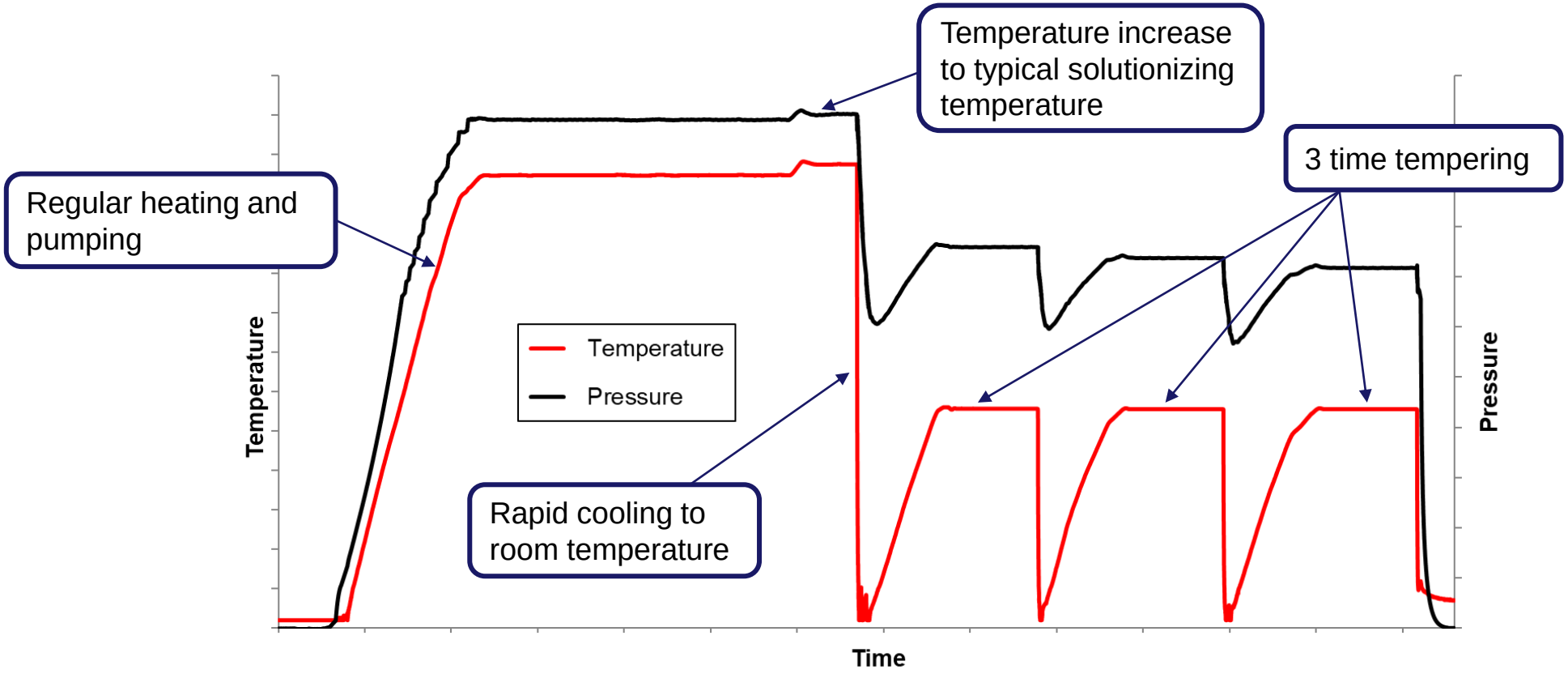


Stop cooling/quenching at a predefined temperature



Modern HIP System Flexibility

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

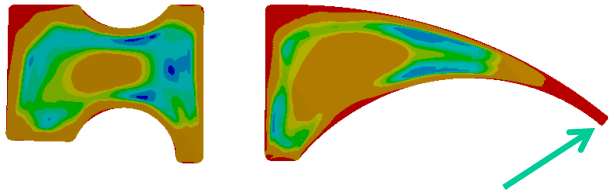


Benefits of HPHT

- The high pressure remains during cooling/quenching
- High pressure gas ➔ high density gas ➔ 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 ➔ Low thermal stresses ➔ Low risk of cracks or distortion
- Performing the heat treatment under high pressure ➔
  - 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

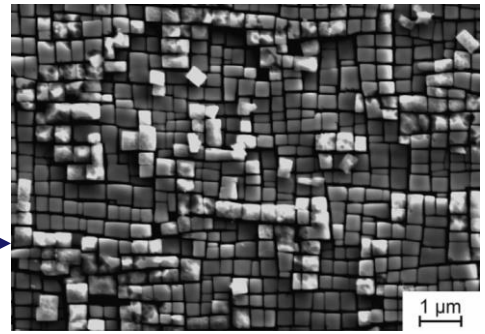
50MPa

Quintus TECHNOLOGIES

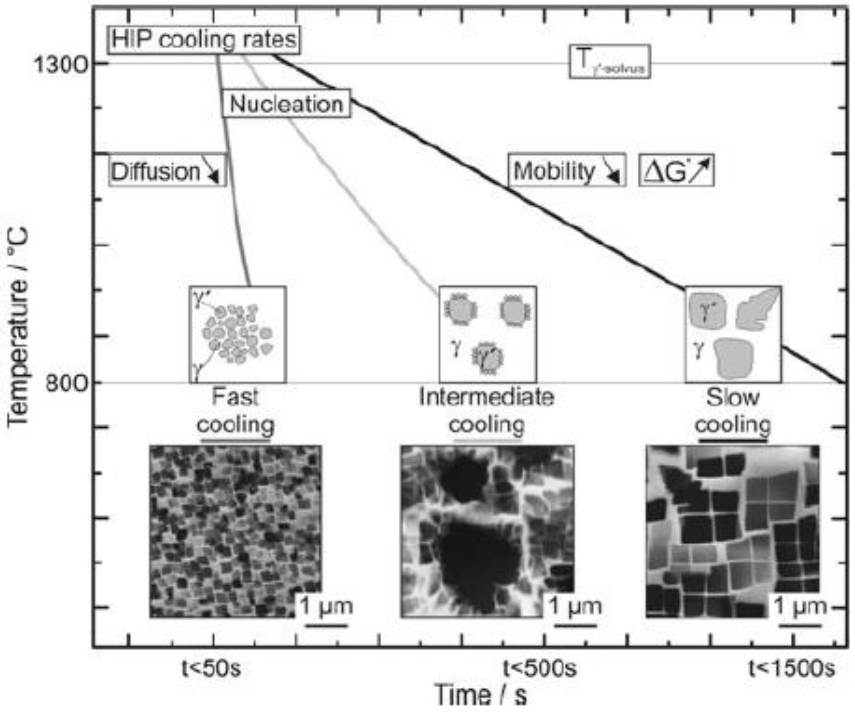
Optimized cooling results in repeatable material properties

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:	>500ºC/min

Quintus® QIH 122

Hot Zone

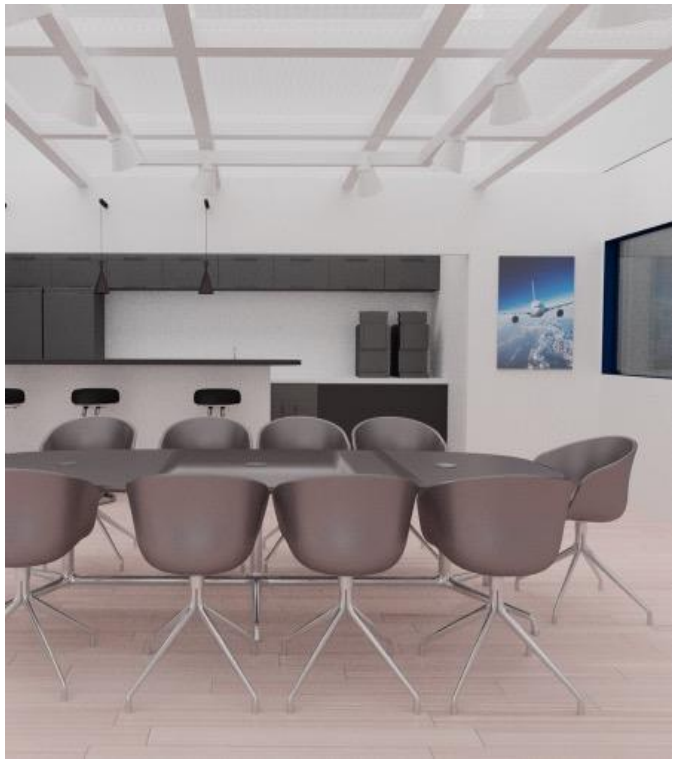
Diameter:	660mm (25.98 inch)
Height:	1750mm (68.9 inch)
Working pressure:	400 to 2,070 bar (5,800 to 30,000 psi)
Max Temperature:	2,000°C (3,632°F)
Cooling rate:	>200ºC/min

Quintus TECHNOLOGIES

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



Quintus TECHNOLOGIES

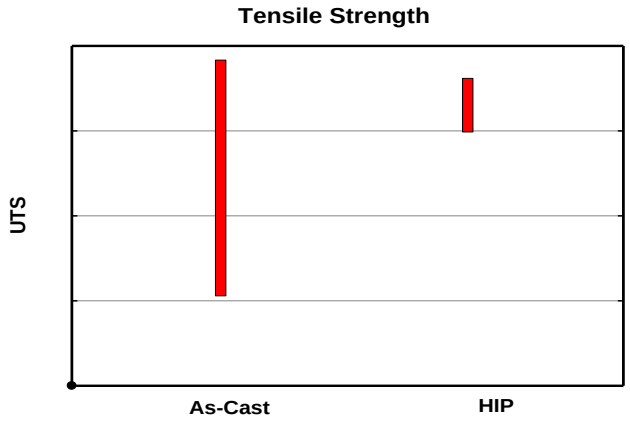
Material property improvements with HIP

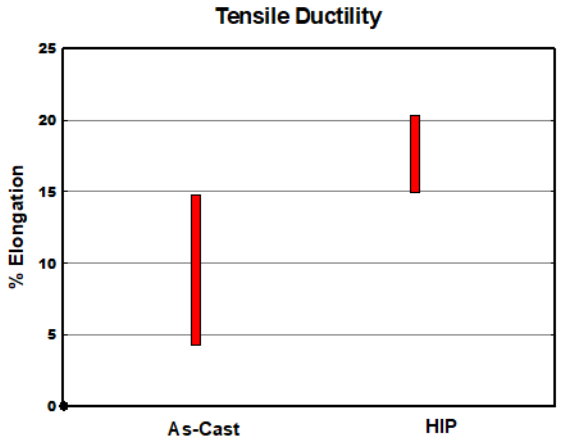
Design advantages from reduced scatter

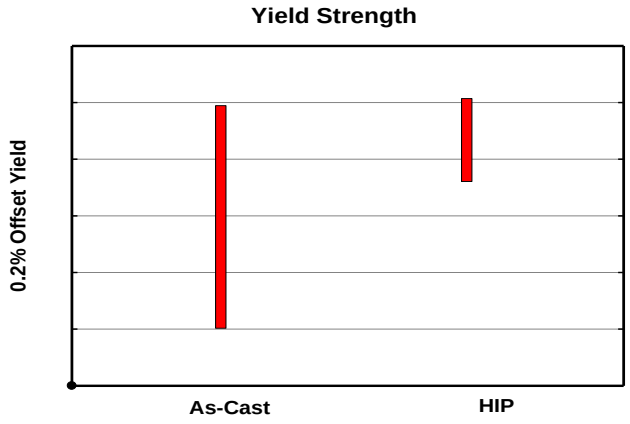
Nickel base super alloy castings

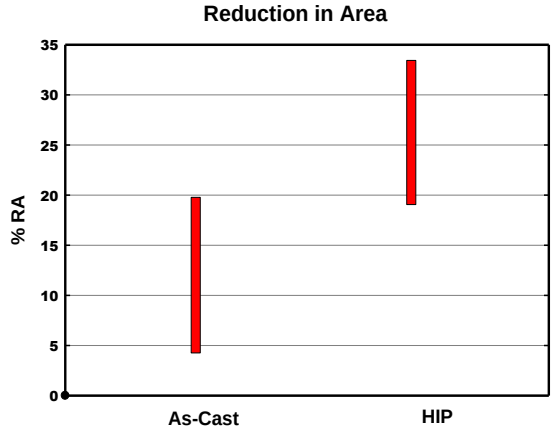
- Scatter in strength values reduced 3-4 fold
- Minimum strength values increased significantly
- Ductility values increased significantly

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



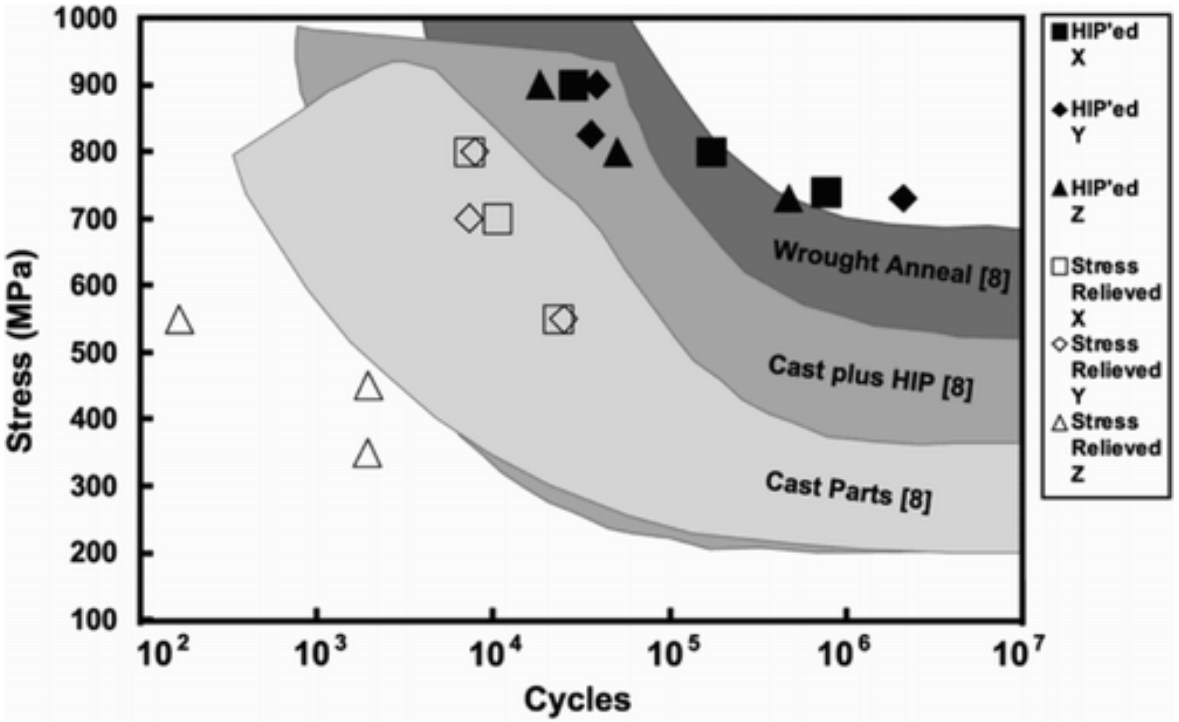






Data courtesy of Howmet Corp.

HIP lifts the fatigue resistance of cast parts as well as AM



P. A. Kobryn and S. L. Semiatin: 'Mechanical properties of laser-deposited Ti–6Al–4V', in 'Solid freeform fabrication proceedings', Austin, TX, 2001.

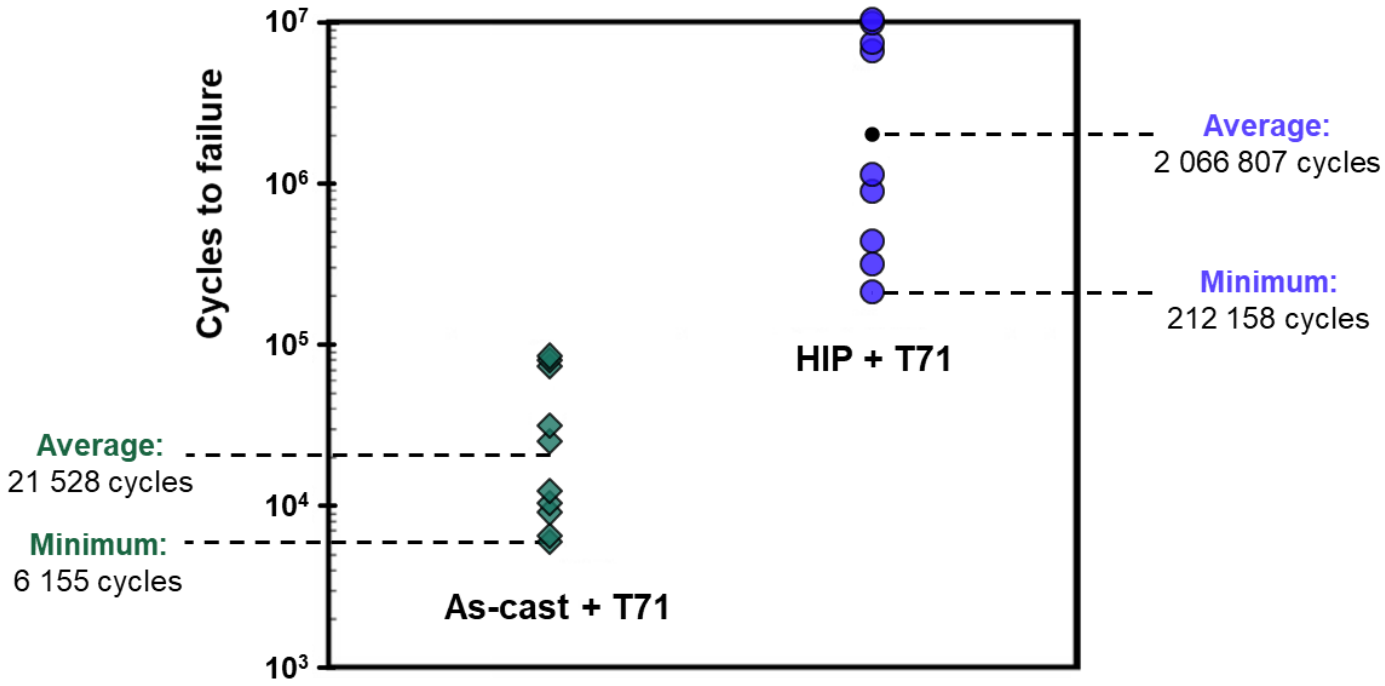
HIP of Cast Material

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

Quintus TECHNOLOGIES

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**



Ref: J. T. Staley Jr et al., *The effect of hot isostatic pressing (HIP) on the fatigue life of A206-T71 aluminum castings,* Materials Science and Engineering A 465 (2007)

Casting Case Studies involving HIP

Main HIP applications

Densification of Products

Improve quality for castings, additive manufacturing, and sintered materials

Diffusion Bonding

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

Courtesy of MTC Japan

Consolidation of Powder

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

Courtesy of Bodycote

High Pressure Heat Treatment

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

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.

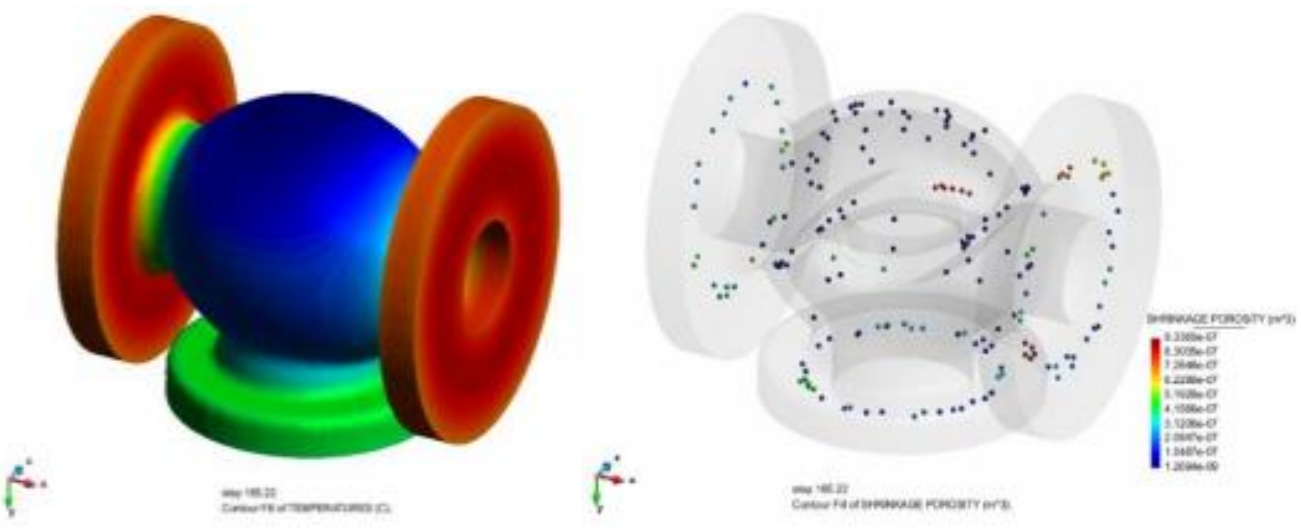
Courtesy of ExOne

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



Thermal-Induced Defects and Optimization of Casting Process
S. Sulaiman, M. Aljermi, M. I. S. Ismail and M.F. Fadzil
International Journal of Mechanical Engineering and Robotics Research Vol. 8, No. 6, Nov 2019

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

Courtesy Midland Impregnations

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

Main HIP applications

Densification of Products

Improve quality for castings, additive manufacturing, and sintered materials

Diffusion Bonding

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

Courtesy of MTC Japan

Consolidation of Powder

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

Courtesy of Bodycote

High Pressure Heat Treatment

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

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)**

Co	Al	Cr	Mo	Ti	Ta	Re	W	Ni
9.7	5.6	6.4	0.6	1.0	6.5	3.0	6.4	Bal.

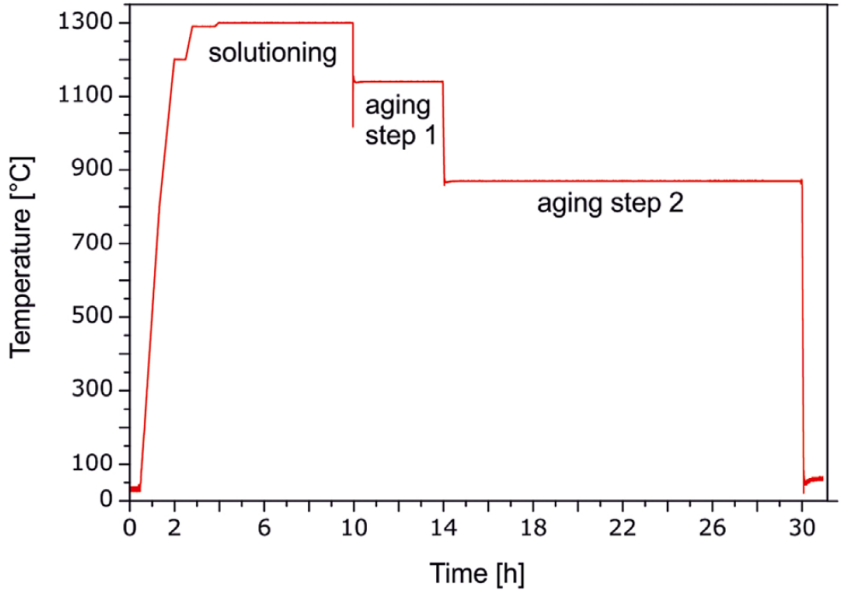
- **Variants studied:**
  - **Heat treated (HT) material**
  - **HIP + HT material (HPHT combined in HIP)**
- **Density, microstructure and high/low temp creep evaluated**

Ref: L. Mujica Roncery, *On the Effect of Hot Isostatic Pressing on the Creep Life of a Single Crystal Superalloys,* Advanced Engineering Materials 18(8), April 2016

Test matrix

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

Combined HIP and HT cycle @100MPa (15000 psi)



Quintus TECHNOLOGIES

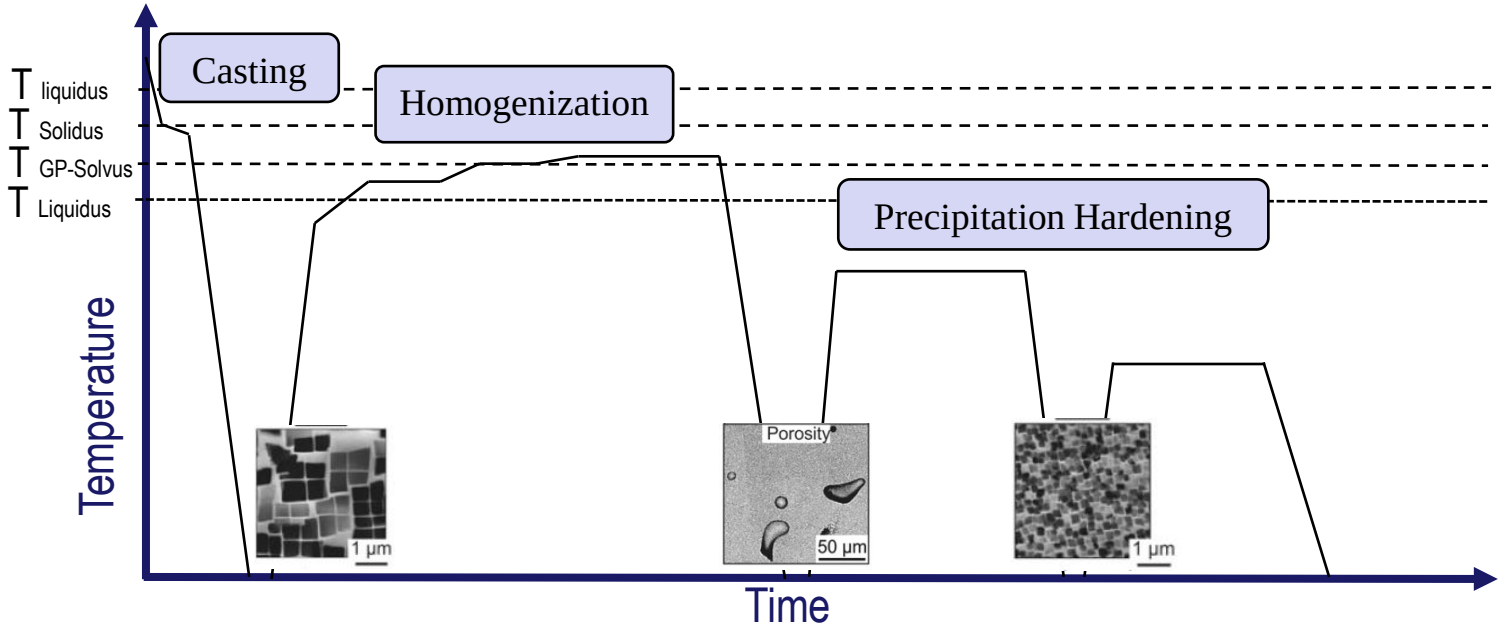
Ni-base Cast Single Crystal

HT Variant #1: Conventional processing

- **Requires 3 main steps**

HT Variant #2: Modern HPHT processing

- **Integrated into single step under pressure**



Ref: L. Mujica Roncery, *On the Effect of Hot Isostatic Pressing on the Creep Life of a Single Crystal Superalloys,* Advanced Engineering Materials 18(8), April 2016

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

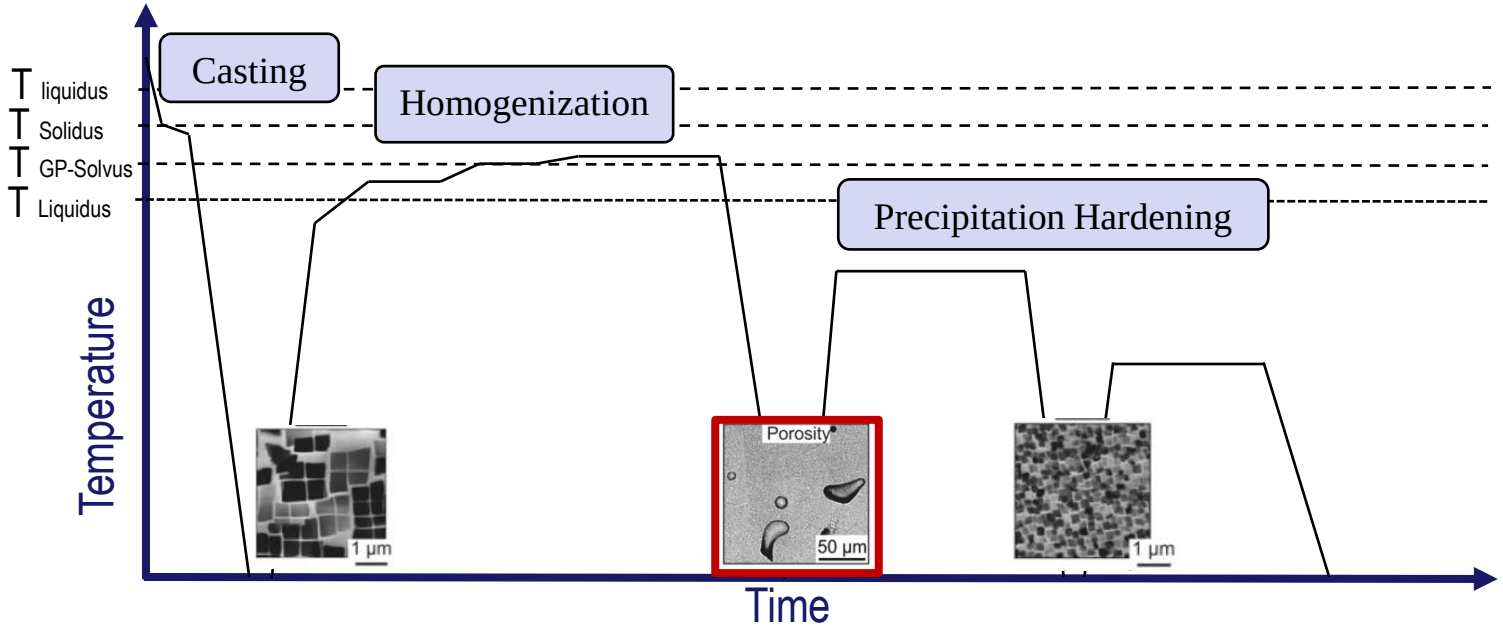
Ni-base Cast Single Crystal

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

Ref: L. Mujica Roncery, *On the Effect of Hot Isostatic Pressing on the Creep Life of a Single Crystal Superalloys,* Advanced Engineering Materials 18(8), April 2016

Quintus TECHNOLOGIES

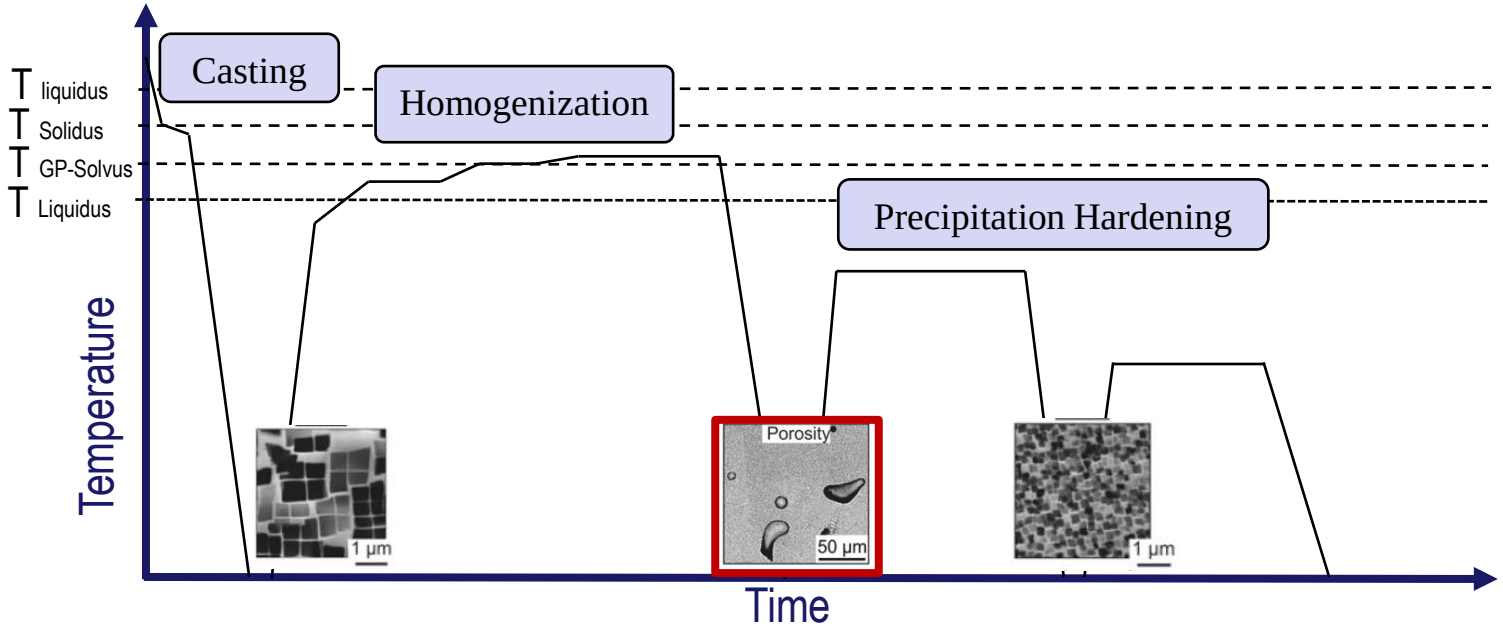
Ni-base Cast Single Crystal

HT Variant #1: Conventional processing

- **Requires 3 main steps**

HT Variant #2: Modern HPHT processing

- **Integrated into single step under pressure**



Conventional HIP integration

- Post casting – doesn't address homogenization porosity
- Post homogenization - requires additional solution

Ref: L. Mujica Roncery, *On the Effect of Hot Isostatic Pressing on the Creep Life of a Single Crystal Superalloys,* Advanced Engineering Materials 18(8), April 2016

Quintus TECHNOLOGIES

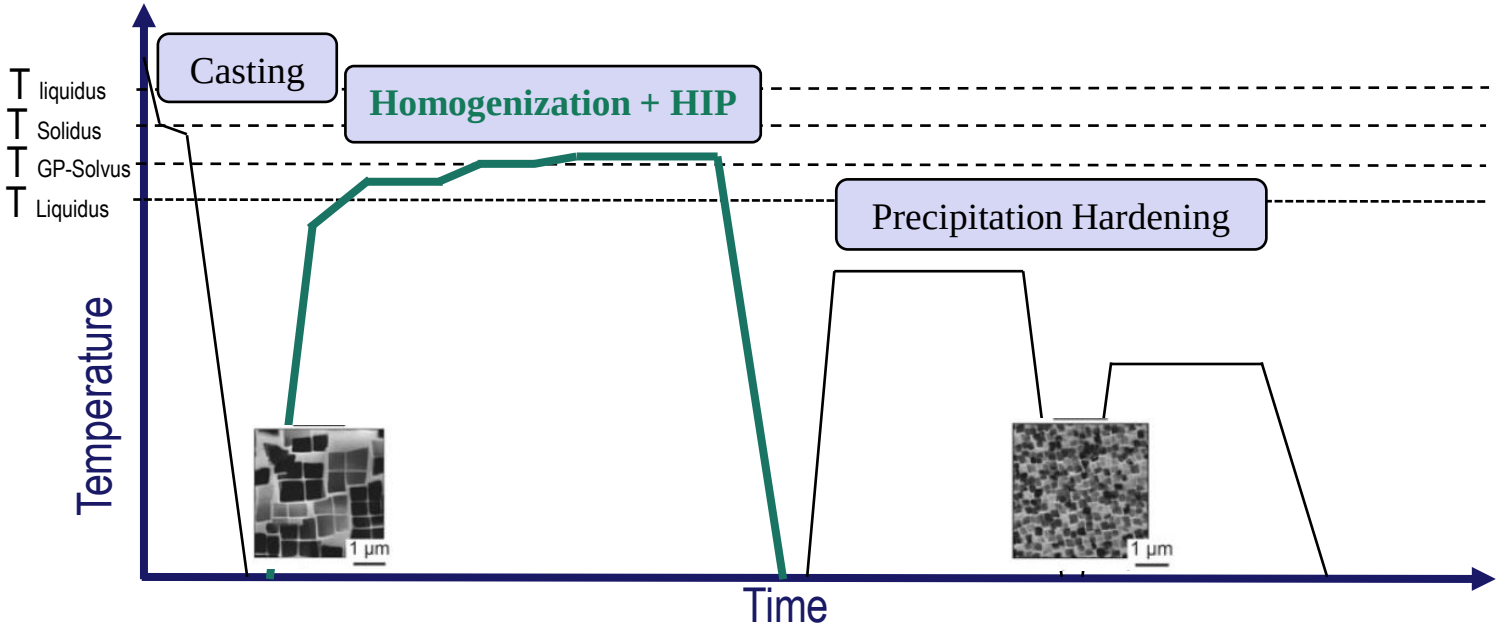
Ni-base Cast Single Crystal

HT Variant #1: Conventional processing

- **Requires 3 main steps**

HT Variant #2: Modern HPHT processing

- **Integrated Homogenization + HIP**



Ref: L. Mujica Roncery, *On the Effect of Hot Isostatic Pressing on the Creep Life of a Single Crystal Superalloys,* Advanced Engineering Materials 18(8), April 2016

Casting

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

Homogenization + HIP

- 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
- **Eliminate both as-cast and homogenization porosity**

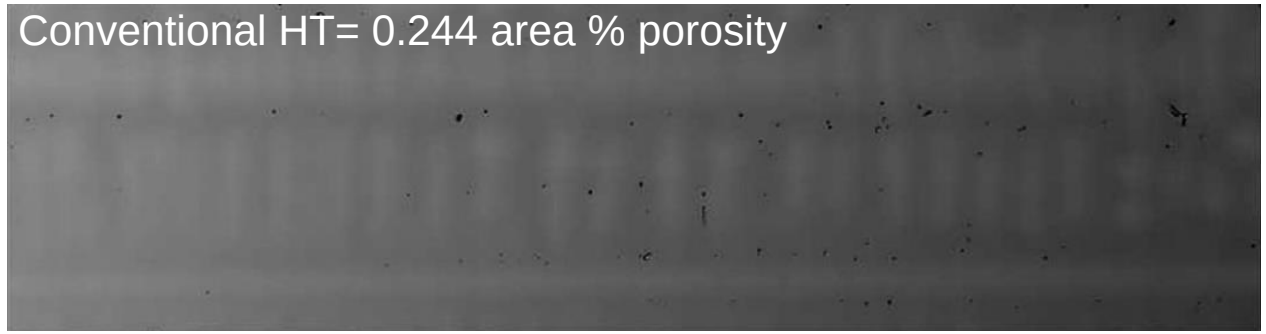
Precipitation Hardening

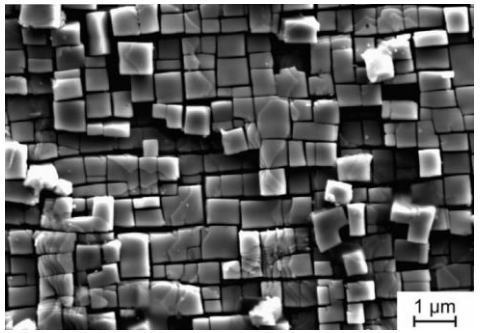
- Performed in 2 steps to optimize the gamma/gamma prime microstructure

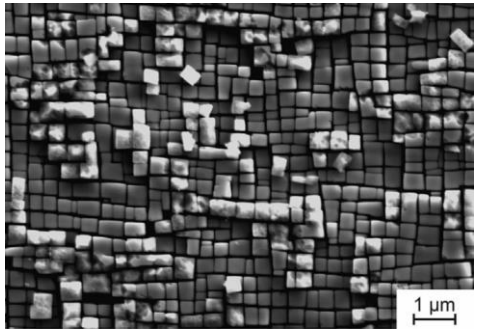
Quintus TECHNOLOGIES

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**







ERBO/1 Variants

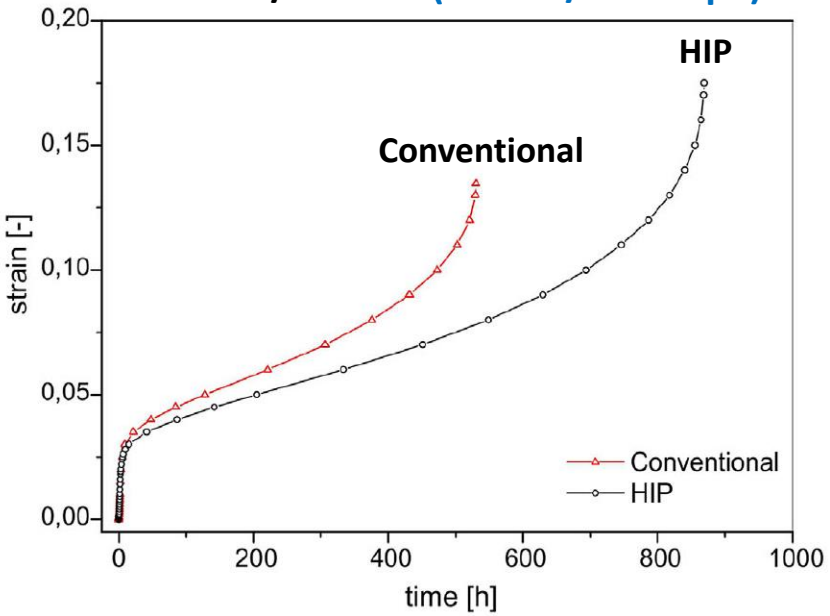
- Same γ'-volume fraction for both variants ~ 75 %
- Finer γ/γ'- microstructure for combined HIP and HT
  - Due to the faster cooling in HIP after solution annealing

Ref: L. Mujica Roncery, *On the Effect of Hot Isostatic Pressing on the Creep Life of a Single Crystal Superalloys,* Advanced Engineering Materials 18(8), April 2016

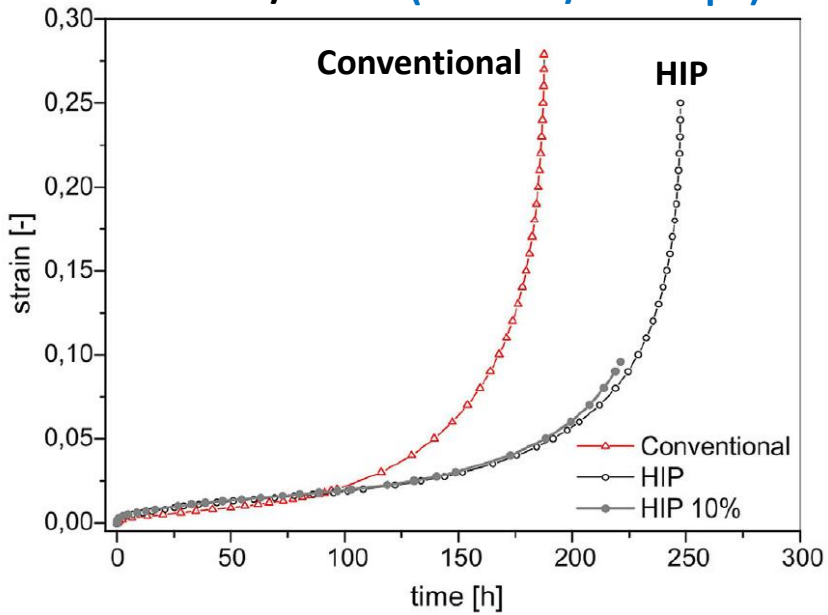
The effect of HIP and HPHT on creep properties of Ni-base SX

- **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 acieved by HIP due to the higher cooling rate**

1382 F / 116 ksi (750 °C / 800 Mpa)



1922 F / 23 ksi (1050 °C / 160 Mpa)

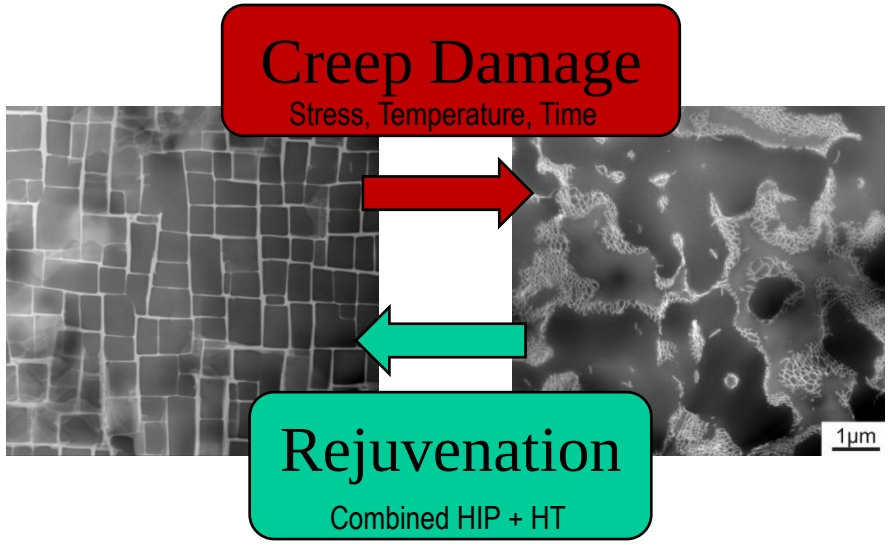


Ref: L. Mujica Roncery, *On the Effect of Hot Isostatic Pressing on the Creep Life of a Single Crystal Superalloys,* Advanced Engineering Materials 18(8), April 2016

HPHT Example: Creep rejuvenation of a turbine blade by HPHT

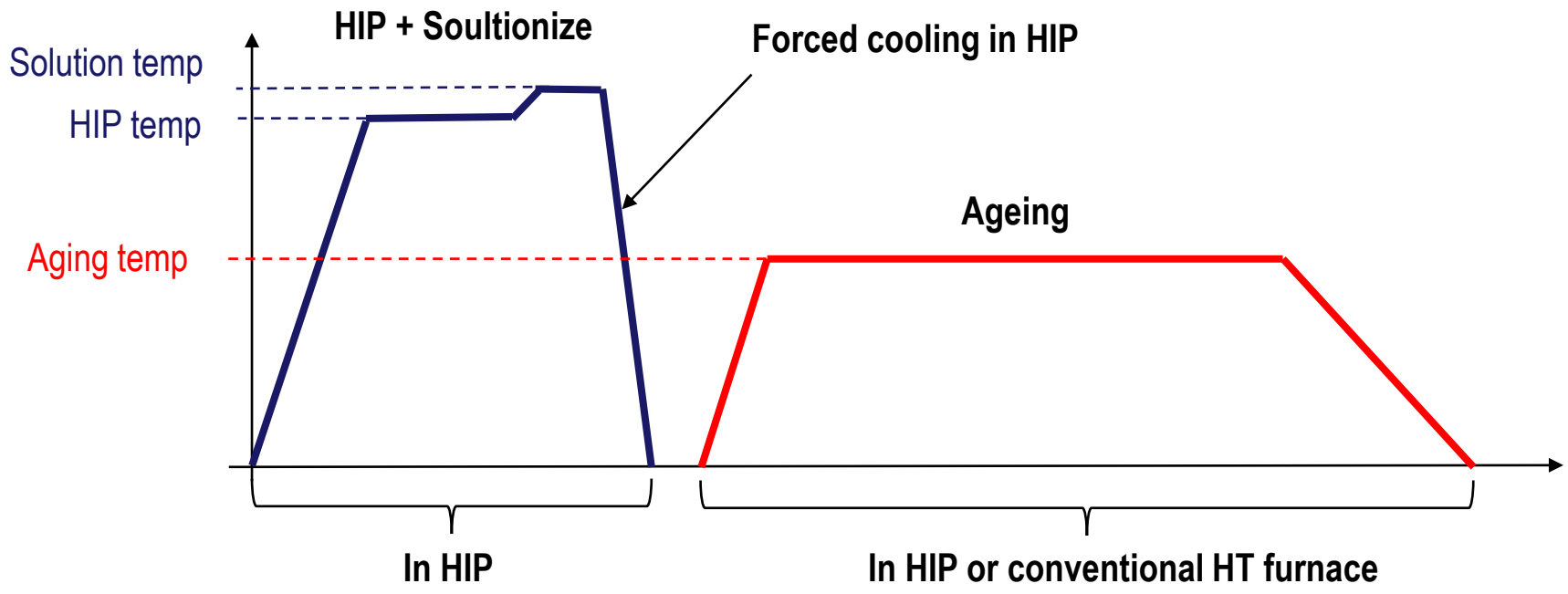
Rejuvenation of turbine blades is commonly conducted using HIP

- 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 γ/γ'-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)



HIP+HT rejuvenation process

- 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

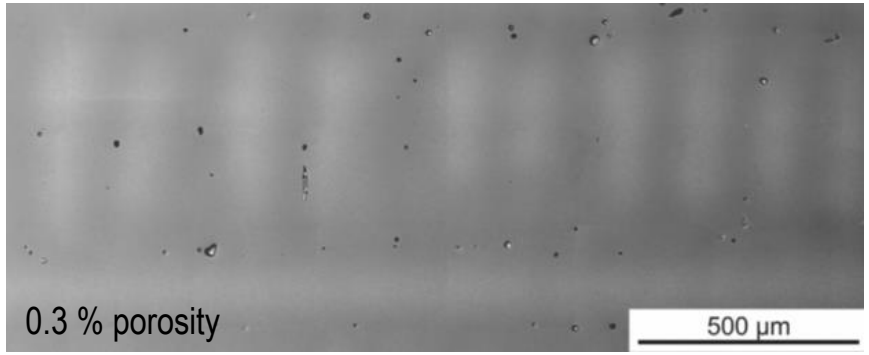


Elimination of creep induced internal porosity

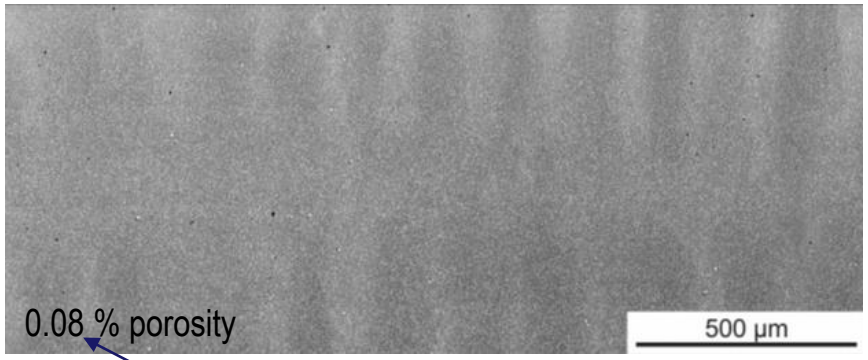
Porosity Evolution:

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

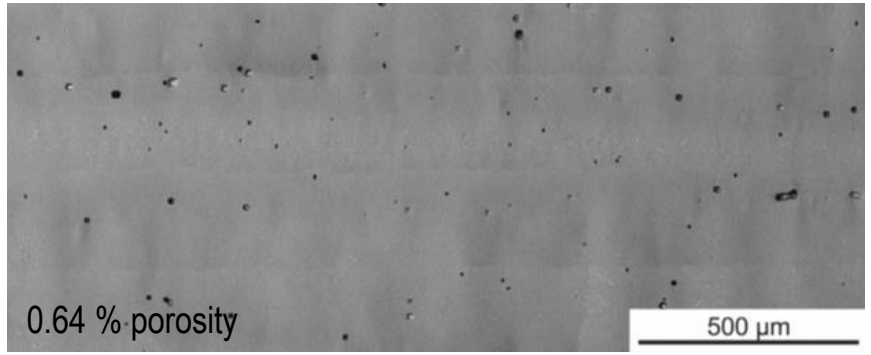
Microstructure before operation (Not HIP:ed)



Microstructure after operation and after HIP+HT rejuvenation



Microstructure after operation



The porosity level in the used and rejuvenated blade is even lower than in the new unused blade

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

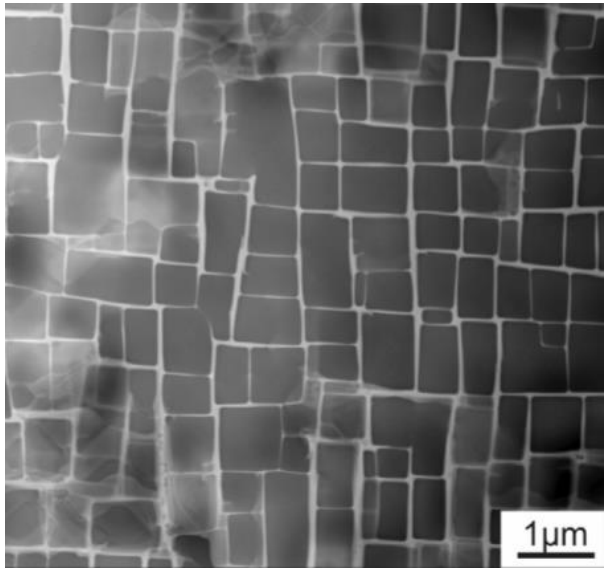
Restoration of γ/γ'-microstructure

Microstructural Evolution:

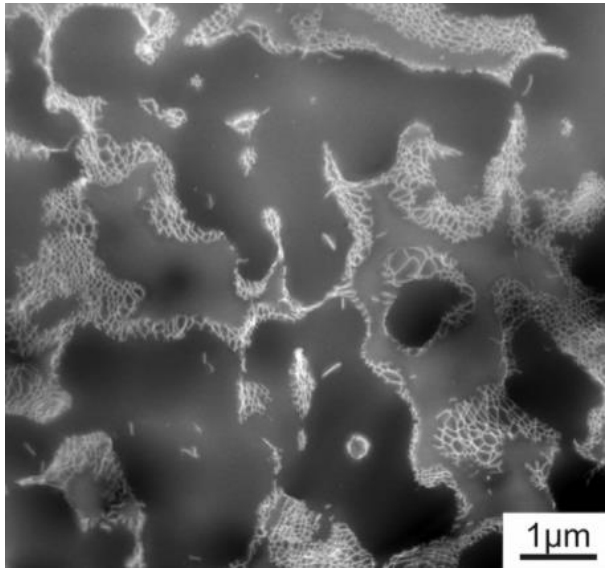
- The γ/γ'-microstructure changes during operation, decreasing the creep resistance of the material
- The HIP+HT process restores the microstucture completly to its initial state

The rejuvenated microstructure is even finer that the for a new unused balde

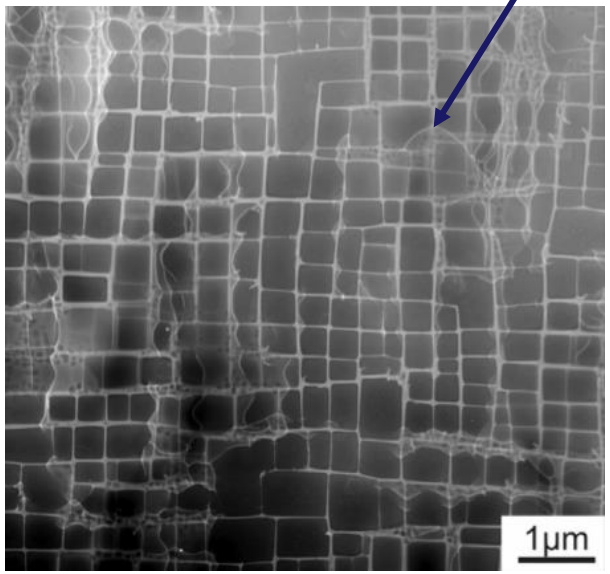
Microstructure of new unused blade



Microstructure after operation (used blade)



Microstructure after operation and after HIP+HT rejuvenation



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

Quintus TECHNOLOGIES

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
  - Perfomed 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

Improve quality for castings, additive manufacturing, and sintered materials

Diffusion Bonding

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

Courtesy of MTC Japan

Consolidation of Powder

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

Courtesy of Bodycote

High Pressure Heat Treatment

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

Thank you for your attention!

Chad Beamer
Applications Engineer
Hot and Cold Isostatic Presses
chad.beamer@quintusteam.com