Benefits of Hot Isostatic Pressing and Heat Treatment

Bodycote

HOT ISOSTATIC PRESSING

North American Locations:

Andover, Massachusetts

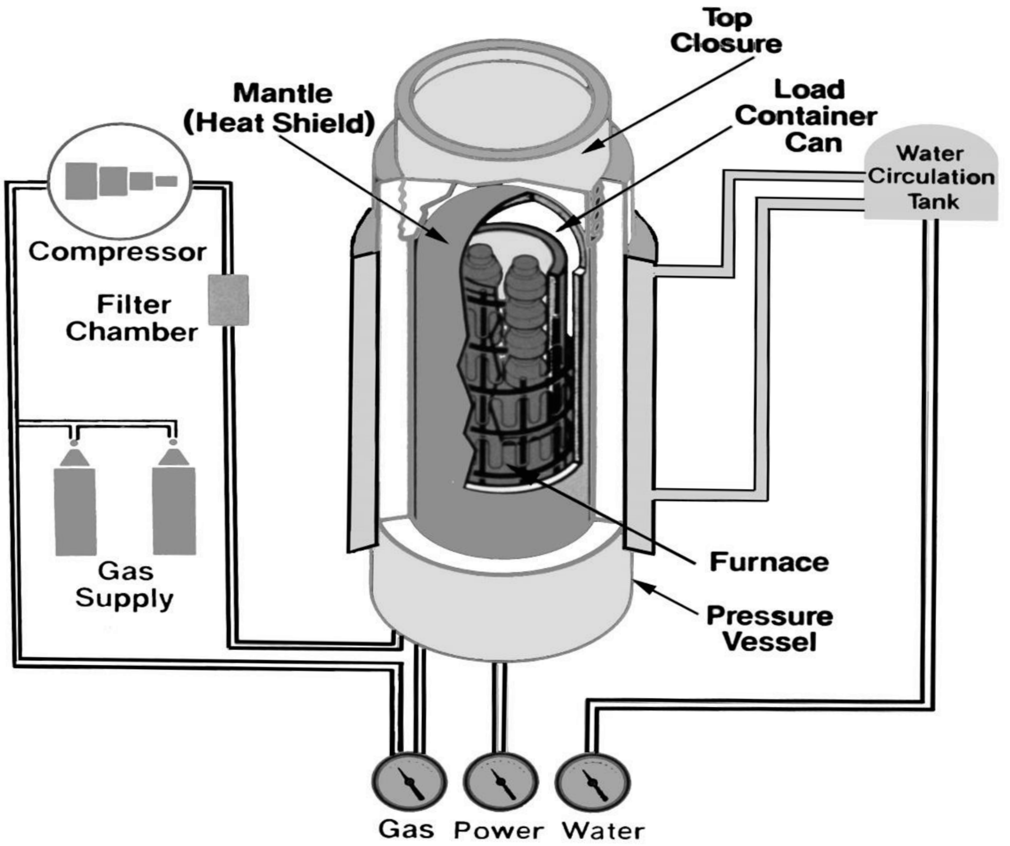
Camas, Washington

London, Ohio

Princeton, Kentucky

What is Hot Isostatic Pressing (HIP)?

The HIP process applies high pressure to the exterior of a part via an inert gas. The elevated temperature and pressure cause sub-surface voids to be eliminated through a combination of plastic flow and atom/vacancy diffusion.



Elimination of Porosity - Macroscopic

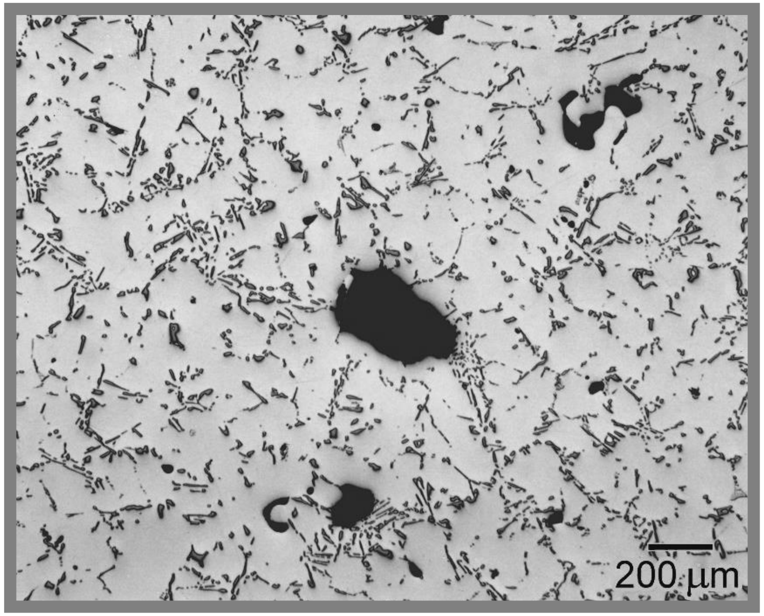
A one-inch hole was machined into two aluminum block halves, which were then welded together along their edges to simulate an internal pore. After HIP, the block was cut in half to reveal fully dense material.

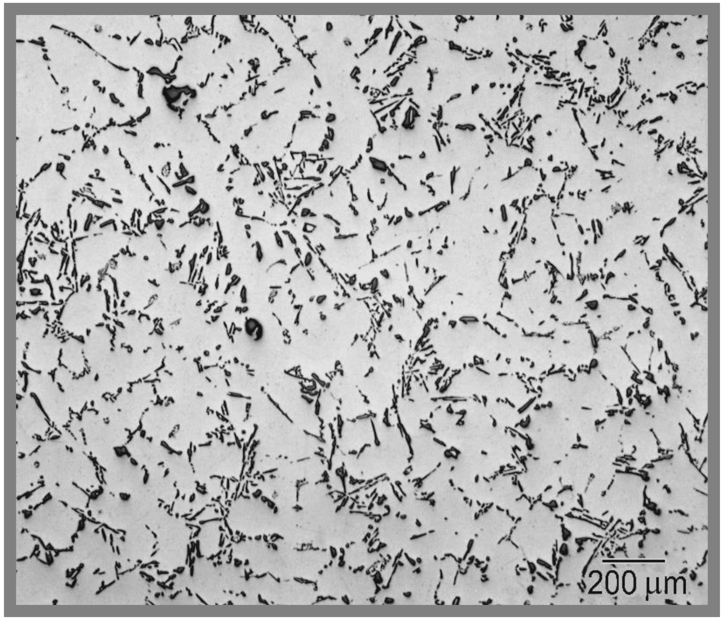
Elimination of Porosity - Microscopic

A356 aluminum casting microstructures

As cast

After HIP

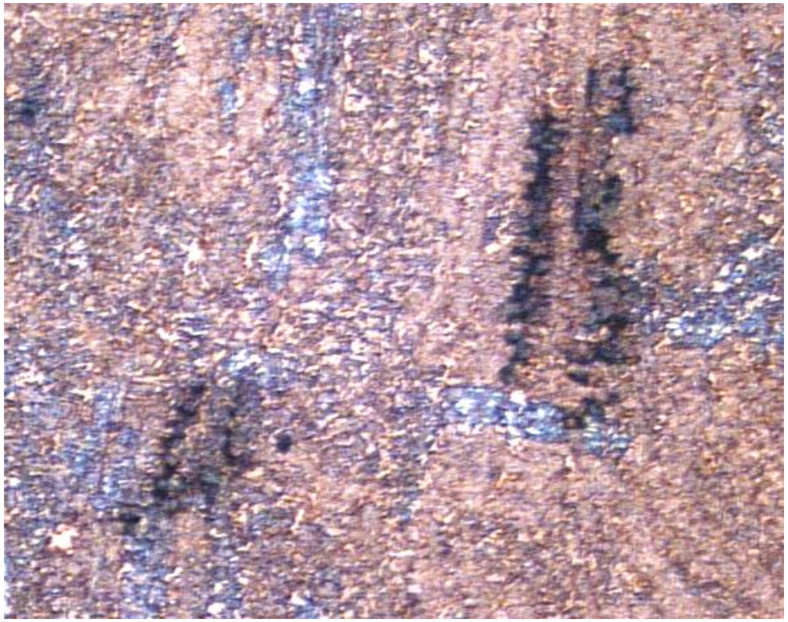




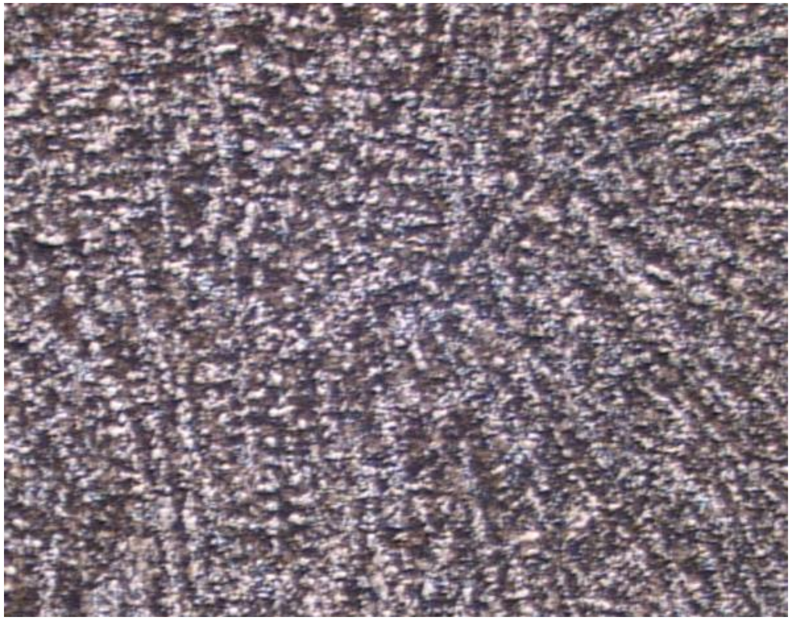
Elimination of Porosity - Microscopic

4140 steel casting microstructures

As cast



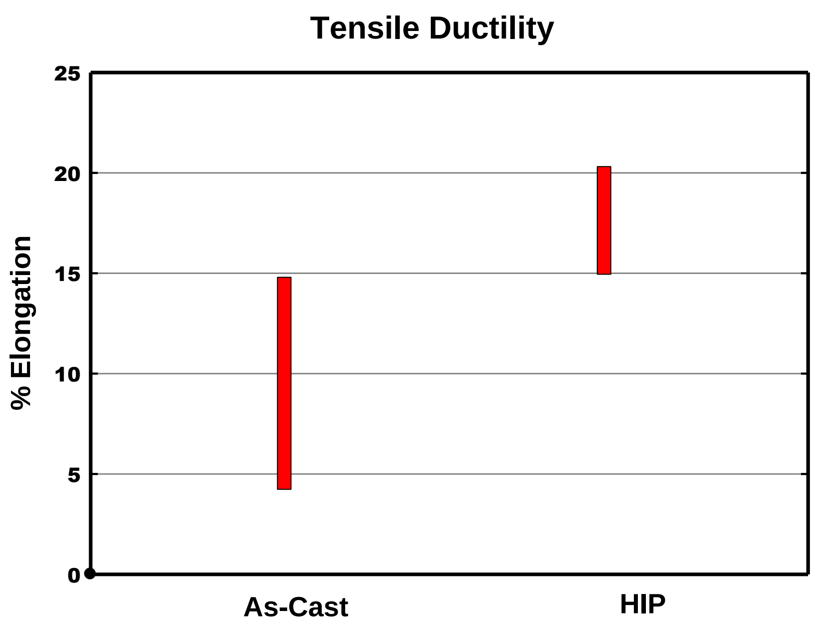
After HIP

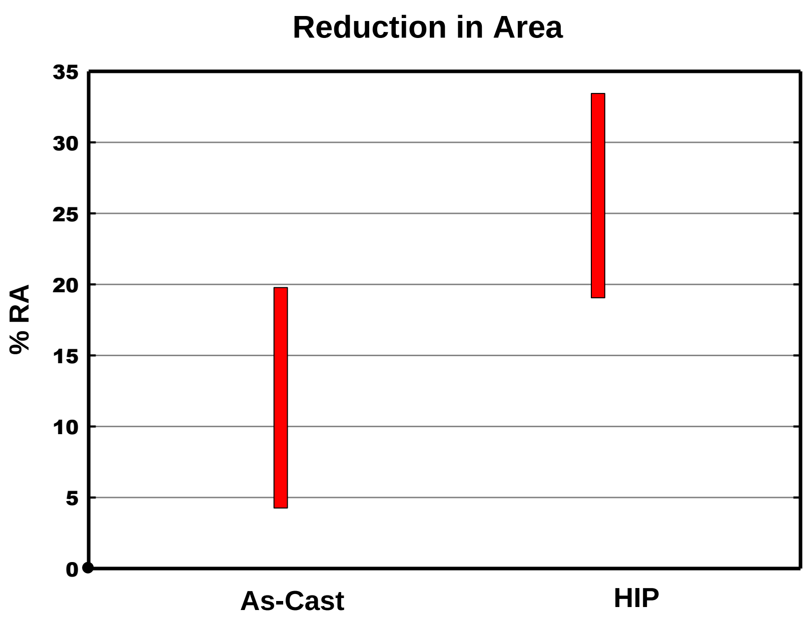


original magnification 25x

Effect of HIP on Casting Properties

Variation in tensile ductility before and after HIP,
for typical nickel-base superalloys

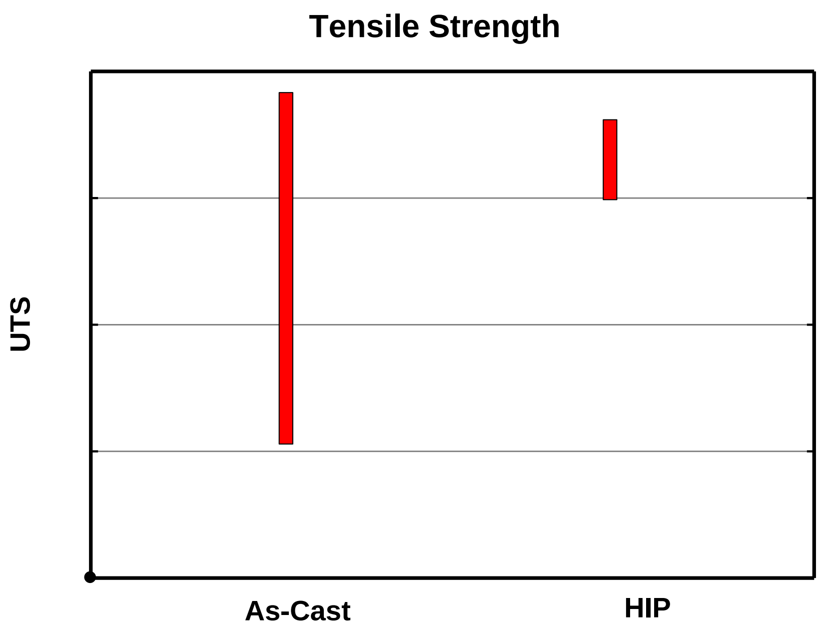


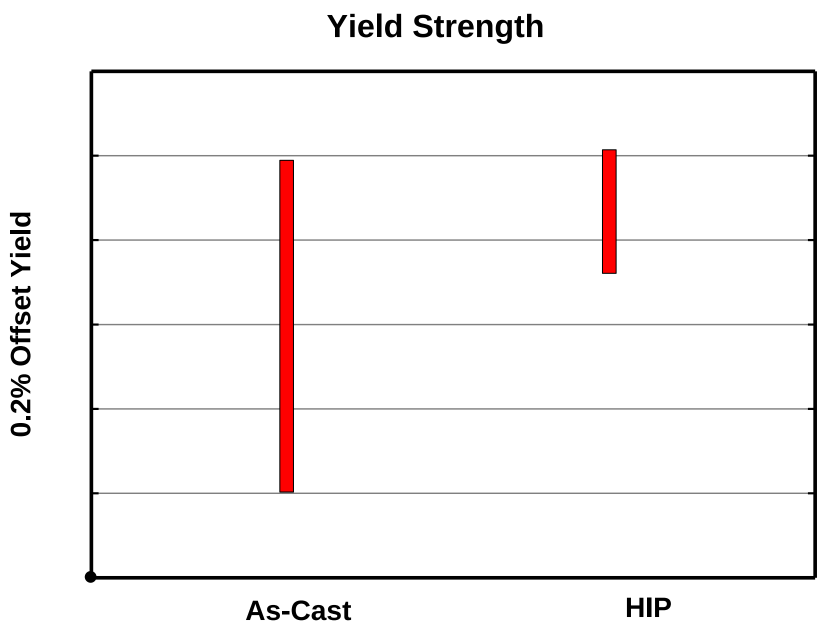


Data courtesy of Howmet Corp.

Effect of HIP on Casting Properties

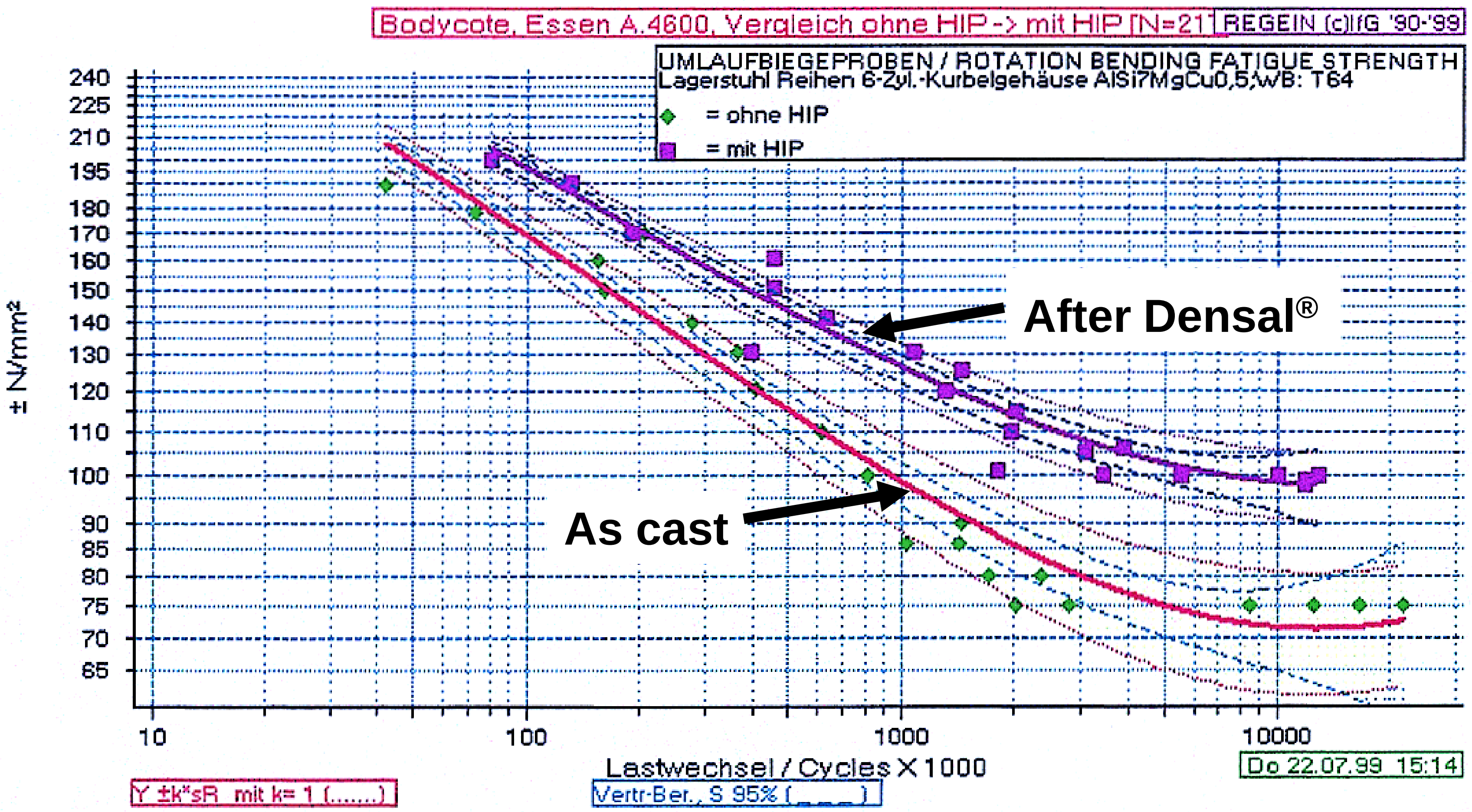
Variation in ultimate tensile and yield strengths before and after HIP, for typical nickel-base superalloys





Data courtesy of Howmet Corp.

Effect of HIP on Fatigue Strength



Gravity die cast aluminum engine block for automotive diesel engine

Reasons to HIP Castings

- Elimination of the microporosity that forms within castings can significantly improve fatigue life, impact toughness, creep rupture strength and tensile ductility.
- Yield and tensile strength are generally not improved but, given a reasonable population of samples, the lowest measured values usually increase with HIP; i.e. the amount of property variation decreases.
- Parts that have failed x-ray inspection can be recovered.
- Removal of porosity improves the as-machined surface finish.
- 100% inspection can be eliminated.
- Elimination of porosity allows vacuum tight metal-to-metal seals.
- Internal cracking can be healed.

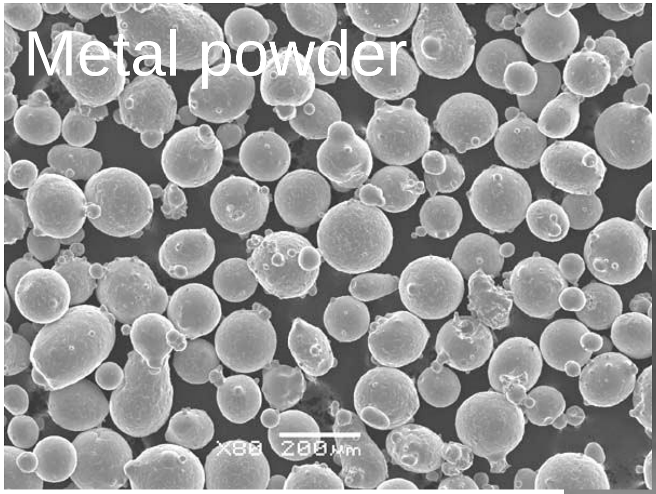
Commonly HIPed Castings

- Turbine engine components
  - Structural castings
  - Blades
  - Vanes
- Orthopedic implants
- Commercial castings
  - Turbocharger wheels
  - Pump bodies
  - Valve components
  - Sterile enclosures
  - High vacuum materials
  - Aluminum, steels, titanium, Ni and Co-based superalloys, stainless steels, ceramics, composites, etc.

Possible HIP Limitations for Castings

- Volumetric Shrinkage
- Surface-Connected Porosity
  - Pressurizing gas will enter pores and hold them open (need to HIP prior to machining).
- Incipient Melting
  - If a compositional gradient (segregation) exists within a cast part, the local melting temperature may be lower than the HIP temperature.
- Eutectic Melting
  - Solid state reactions between castings and support tooling must be considered.
- Creep Deformation
  - Care must be taken with thin wall section parts.

Additional Applications for HIP



HIPed PM Near Net Shapes

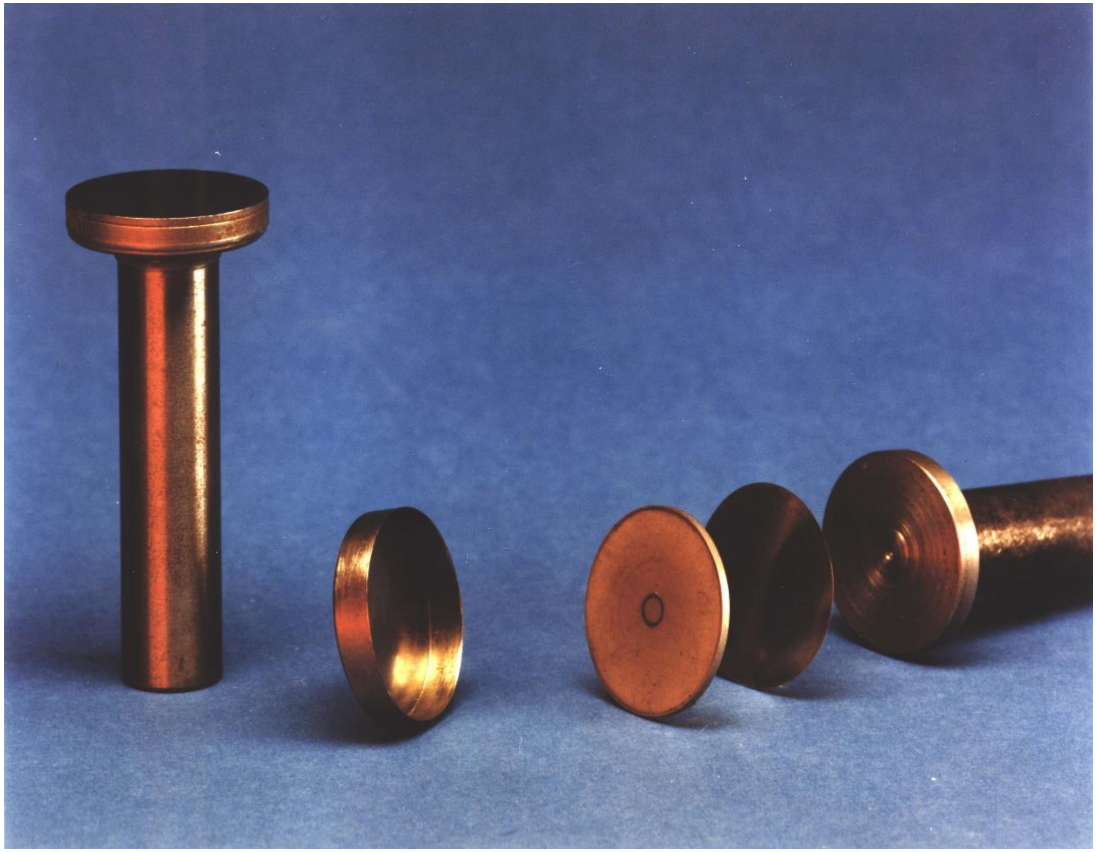
Cross-section of sheet steel fabrication used to encapsulate powder

Titanium alloy HIPed PM finish-machined part

Additional Applications for HIP

HIP Cladding – solid/solid, solid/powder, powder/powder

HIP bonding a tungsten carbide wafer onto a mild steel diesel valve lifter (solid/solid)



Bodycote HIP Resources in N.A.

- 4 locations with 22 production HIP vessels
  - Pressure capabilities to 45,000 psi
  - HIP temperatures to 3600°F
  - Vessel sizes from 7” dia. x 12” height to 64” dia. x 100” height
- Certifications
  - NADCAP
  - ISO 9001, ISO 14001 and AS9100

Heat Treatment - History

- Earliest evidence of heat treatment was on a dagger forged and tempered in Egypt around 1350 BC

- Blacksmiths and metalworkers were associated with “Natural Magic” to impart the desired properties in armor and weapons

- 1540 - First publication on Metallurgy
  “De la Pirotecnica” by A.V.Biringuccio remarks on the importance of –
  the ‘color (temperature) of the metal before quenching ’ and gave secret information on the ‘best’ quench media which included water , oil , jus d’herbe , vinegar and urine

Heat Treatment - History

- **1563 – a paper on Heat Treatment of Steel read before the 'Society of' Engineers' gave another recipe for a Quenchant**
  "Take snayles and first drawn water of a red die, of which water, being taken in the first month of harvest when it raynes, boil it with the snayles, then heat your iron red-hot and quench it therein and it shall be as hard as steel

- **In 1632, Josh Modi, a 'Crucible Steel maker had explained that steel was simply alloy of iron and carbon. Changing the percentage of carbon combined with proper heat treatment would allow the steelmaker to tailor specific steel for specific uses, from cutlery to cannon,**

- **Armaments and weapons were the greatest driver of the development of the process up until the start of the Industrial revolution**

Why is Heat Treatment necessary?

Heat Treatment is used to modify the properties of materials (usually metals) to give specific characteristics.

The effects of Heat Treatment on properties can fitted into four basic categories -

1. Modification of undesirable internal structures or the effects of machining working or machining. Processes include:
    - Annealing
    - Normalizing
    - Stress Relieving
2. Development of specific mechanical properties including strength, ductility, fatigue and creep resistance
    - Harden and Temper
    - Solution and Aging (Precipitation) Treatments
    - Cryogenic Treatments

Why is Heat Treatment necessary? additional processes

3. **Modification of surface properties increasing wear, fatigue, scuffing and corrosion resistance**
   - Carburizing (Gaseous and Low Pressure processes)
   - Carbonitriding
   - Nitriding (Gaseous, Plasma and Fluidised bed)
   - Nitrocarburizing

4. **Metal Joining – includes**
   - Atmosphere and Vacuum Brazing
   - Electron Beam Welding

WHY IS IT IMPORTANT (OR EVEN CRITICAL) TO HEAT TREAT CORRECTLY?

The Jesus Nut

So what is the Jesus Nut ?

It's the nut which holds the rotor blades onto the main drive shaft of a helicopter

It is made from MIL-S 46850 (AMS 6514) Maraging steel Aged to 200 kpsi minimum Tensile Strength

So why Jesus Nut? –

The story goes that Igor Sikorsky, the developer of the modern helicopter was a religious man and his thoughts were that if the nut ever failed inflight, the next person the pilot would see would be Jesus

IF YOU DON'T BELIEVE IT GOOGLE 'JESUS NUT'

ANNEALING

Furnace type – Atmosphere / Air or Vacuum

Process Outline – can be applied to ferrous or non ferrous metals by heating to and holding at a suitable temperature (typically ½ to $^{2}/_{3}$ melting point) followed by cooling at an appropriate rate – depending on particular metallurgical characteristics. Process lends itself to bulk treatments in large furnaces

Purpose – to soften materials or to produce desired changes in structure and properties, for example Steels are 'annealed' to facilitate cold forming

Applications

- Raw Material
- Forgings and Castings
- Semi finished parts
- Facilitating cold work
- Improving machineability
- Improve ductility

Stress Relieving

Furnace type – Air or Vacuum

Process Outline – Applies to Ferrous and non Ferrous materials and is carried out at a low non critical temperature (does not have a negative effect on properties)

Purpose – To remove stresses locked into the material from manufacturing operations for example machining, cold working, fabrication or welding Post weld Stress relief can also improve fracture toughness. Failure to remove internal stress can lead to distortion problems if parts are heat treated at a later stage

Application

- Near finished machined parts
- Cold worked or formed parts
- Welded fabrications

Solution Treatment

Furnace Type Air/Vacuum –

Process Outline – Ferrous (PH Steels) and non ferrous materials (Nickel based Heat resisting alloys and alloys of Aluminum and Titanium) respond to Solution treatment by heating to elevated temperatures (>1925^{0}F PH Steels, >2100^{0}F Heat resisting alloys, ≈ 925^{0}F Aluminum and 1350/1650^{0}F Titanium) followed by cooling at specific rates. Al and Ti alloys need to be Water Quenched although some will respond to Forced Air Quenching or Gas Fan Quench in a Vacuum Furnace.

Purpose - First stage of a multi-stage process (others include low temperature stabilization and ageing) putting material into a condition from which the desired properties will be developed by an aging (also called precipitation) treatment

Applications

- None in the Solution treated condition
- Final properties are developed by aging

AGING OR PRECIPITATION Defined

Furnace Type Air/Vacuum -

Process Outline – Treatment carried out on previously solution treated material at a temperature below the original solution treatment temperature 850/1100^{0}F PH Steels, 1200/1650^{0}F Heat resisting materials, 250/475^{0}F Aluminium alloys, 825/1400^{0}F Titanium alloys

Purpose - To develop specific mechanical properties including creep, fatigue and stress rupture characteristics

Applications

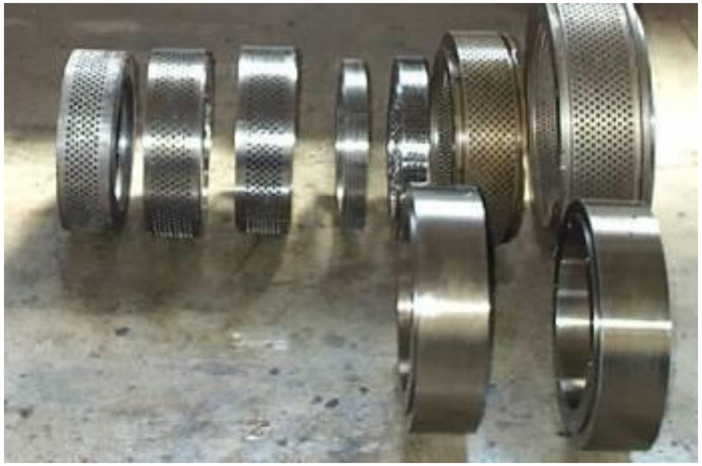
- Mainly Aerospace/IGT applications including turbine blades, casings, landing gear, helicopter rotors, fasteners, welded fabrications, airframes pressure vessels

Heat Treatment to Improve Mechanical Properties of Metals

- Increase tensile strength
- Improve ductility
- Improve resistance to fatigue
- Increase hardness
- Increase toughness

Do all of the above at the same time

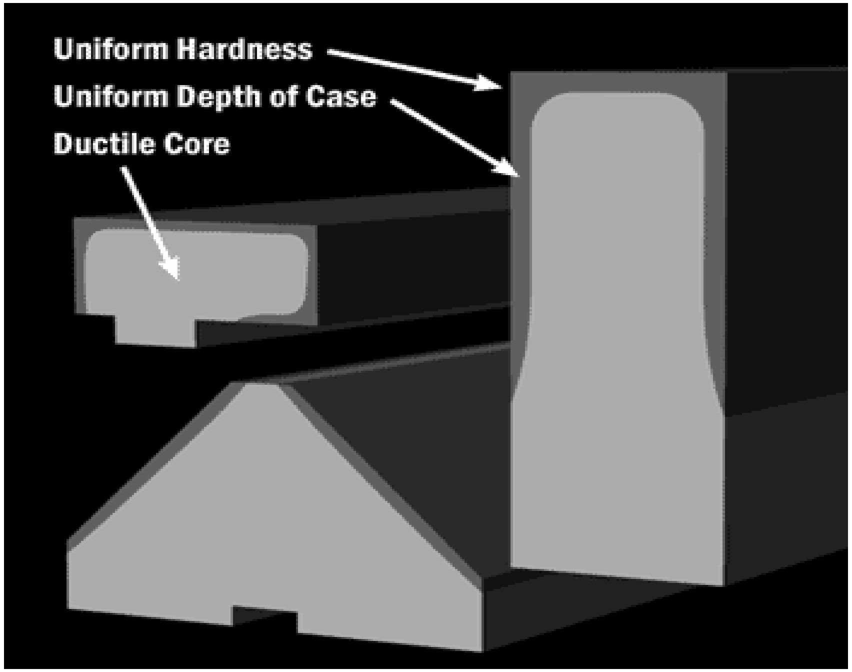
- To reduce mechanical properties
- To make the material more pliant for cold forming
- To make the material more machineable



Heat Treatment to Improve Mechanical Properties of Metals

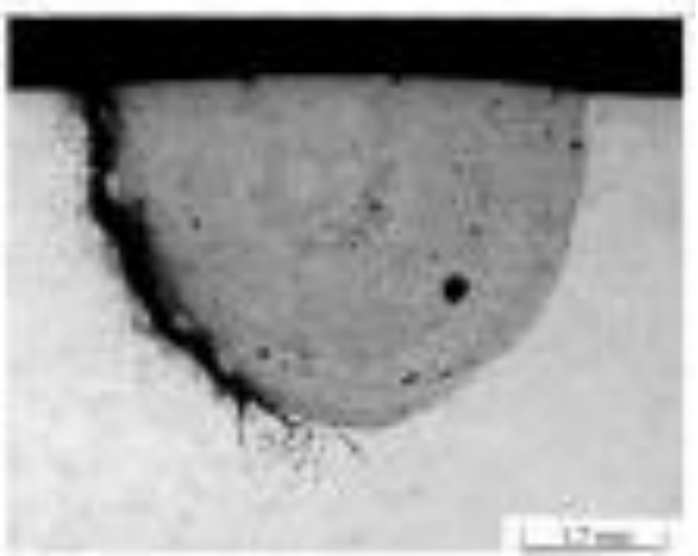
- To make the material more metallurgically stable
- Some metallurgical processes will occur naturally over time with undesirable consequences. It is often better that they are deliberately induced beforehand.

- To make the material more wear resistant



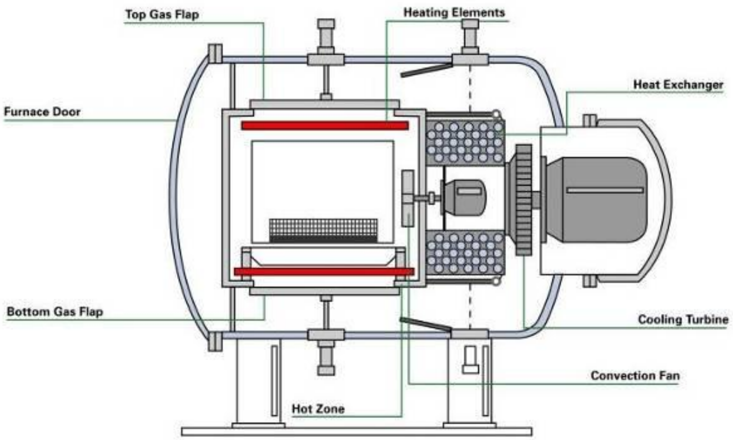
- To prevent cracking

As in Post Weld Stress Relieving



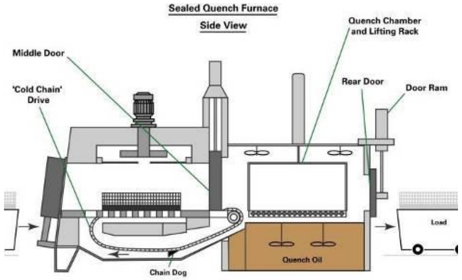
Furnace Types – Vacuum Furnaces

All metal Interior Vacuum furnace



Large Bottom Loading Vacuum Furnace with Graphite Interior

Furnace Types – Atmosphere Furnaces



Integral Quench Furnace operates using an Atmosphere gas produced from air/methane

'Pit' Nitriding Furnace operates using an atmosphere produced by breaking down Ammonia into its constituent Hydrogen and Nitrogen

ATMOSPHERE / AIR TREAMENTS

Hardening and Tempering
Carbonitriding
Normalizing
Nitriding
Sub-critical annealing
Stress relieving
Carburizing
Carbon Restoration
Annealing
Nitrocarburizing
Spheroidizing
Precipitation and Aging
Solution Treatment in Air (Titanium and Aluminum)

Limitations for Atmosphere and Air Furnaces

- Cost of spares and maintenance
- Toxic hazards of Nickel based catalysts used in Gas generation
- Generator / reactor down time affects furnace productivity
- Lost time at start up producing a stable gas composition
- Atmosphere gases or feedstock are hazardous, combustible or potentially explosive

What is an Atmosphere ?

Protective atmospheres

- Usually ‘Inert’ gases including Nitrogen and Argon
- Used to prevent unwanted surface reactions between material being processed and furnace ‘Atmosphere’ – for example oxidation of machined parts
- Care needs to be taken over the description ‘Inert’ – gases like Nitrogen can react with some materials resulting in negative consequences – for example Titanium
- The only truly ‘Inert Gas’ is Argon, which is expensive

Air as an atmosphere

- Greatest risk in air treatments is oxidation of material surface which is dependant on temperature and varies from discoloration at low temperatures to heavy scaling at elevated temperatures

Is VACUUM an atmosphere ?

Q- What is a Vacuum ?

A - ANY PRESSURE WHICH IS BELOW ATMOSPHERIC PRESSURE

- Absolute Vacuum where nothing exists is neither attainable or desirable
- Intergalactic space exhibits a pressure of 10^{-23} mbar
- Majority of Vacuum Heat treatment carried out between 10^{-1} and 10^{-5} mbar pressure (1/10000 to 1/100,000,000 of Atmospheric pressure)
- Pressure level itself is not the controlling factor – the pumping system removes air from the furnace – effectively diluting the air composition in the furnace
- It is the composition of the residual gas at that particular pressure which controls the metallurgical characteristics of the 'atmosphere'
- Evacuating the furnace to 10^{-3}mbar (1/1,000,000 Atmospheric pressure) dilutes composition of air by 10^{6} (if atmospheric pressure = 10^{3}mbar)

SO VACUUM CAN BE CONSIDERED AS AN ATMOSPHERE

A GUIDE TO LOW PRESSURE





Location	Altitude	Pressure as a fraction of Atmospheric
Sea Level	**0 m**	**1/1** 1013 mbar
Sky Diver	**4600 m** (15,000ft)	**1/2** 500 mbar
Summit of Mt Everest	**8848 m** (29029ft)	**1/3** 330 mbar
International Space Station	**350,000 m** (1148291ft)	**1/100000** 10^{-2} mbar
Intergalactic space	**---**	**1/100000000 to 1/10000000000000000** 10^{-8} to 10^{-16} mbar

VACUUM is an Atmosphere but -

Because Nitrogen and Oxygen are still available, even though at a very low level, problems can arise -

- **Oxidation -** depends on the reactivity of material being treated with the amount of oxygen in the furnace at the processing pressure. Only really effects metals with a high attraction to Oxygen – example Titanium

- More often surface oxides present on product before treatment are broken down during processing – which is why product can come out cleaner than it goes in.

VACUUM is an Atmosphere but -

- Alloy loss (depends on pressure and temperature)

  Example – If Stainless Steel Stampings are Annealed at 1925^0F and a Vacuum Level10^{-3} mbar pressure they will lose Chromium from their surface. This will reduce corrosion resistance. It also causes parts to stick together. It can also effect highly alloyed Tool Steels

- It can be avoided by treating the pressings at a pressure higher than 10^{-3} mbar. Treating at 10^{-1}mbar significantly reduces Chromium loss. This is known as treating under "Partial Pressure"

VACUUM TREATMENTS

- Hardening and Tempering
- Normalizing
- Solution Treatments
- Vacuum Degassing
- Carburizing (LPC)
- Annealing
- Stress relieving
- Precipitation and Aging
- Metal joining (Brazing)

Limitations

- Cost of spares and maintenance
- Cleanliness of parts prior to processing is critical
- Heat Transfer below 1000^0F is inefficient without convection
- Oxidation and alloy loss are potential issues depending on vapour pressure and vacuum level
- High purity quench gases are expensive (particularly Argon)
- High quench rates suitable for heat treating alloy steels require high pressures (up to 10 bar) and large gas volumes

Contacts

Albert Sarabia
Albert.Sarabia@Bodycote.com
Esra Cankaya
Esra.Cankaya@Bodycote.com
Paul Dymond
Paul.Dymond@Bodycote.com
Dave Ochar
Dave.ochar@Bodycote.com