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Hot Isostatic Pressing: Today and Tomorrow

Franz X. Zimmerman
Jerry Toops
Avure Technologies, Inc.

Abstract:

Technological advances in Hot Isostatic Pressing (HIP) are creating a new generation of application opportunities to improve the performance and durability of critical parts and materials. New press and furnace designs, uniform rapid cooling capability, and digital control techniques have shortened cycle times significantly. Presses have nearly doubled in size in the past 10 years, dramatically reducing per-unit processing costs. Even larger systems are on the horizon, limited in size only by transportation realities. This will allow densification of ever-larger products and batches, cutting costs and helping customers to grow their competitive advantage. HIP is today more viable and affordable than ever for producing the strong, long-lasting products that are increasingly demanded by globally competitive manufacturers in all kinds of industries.

Background

In the mid-1950s, gas pressure bonding, now called Hot Isostatic Pressing, was conceived by researchers at the Battelle Memorial Institute's Columbus, Ohio laboratory. These scientists were challenged with developing a method of bonding zirconium to zirconium-uranium alloys to be used as nuclear fuel elements. The performance requirements for this type of cladding could not be met with existing conventional methods.[1] This research resulted in the first production use of gas pressure bonding at Westinghouse for the flat plate fuel elements applied in the pressurized water reactor.

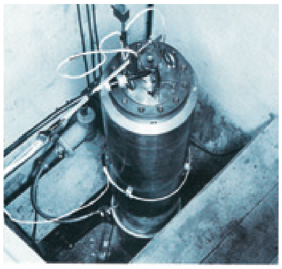


Figure 1. The first cold-wall gas pressure bonding vessel (now called HIP) installed and operated by Battelle in 1956.

At about the same time, ASEA-Sweden employed an ultra-high pressure process to make the first synthetic diamonds in the world, transitioning graphite to diamond at pressures approaching 1 million psi (7,000 MPa). A wire wound vessel and frame was subsequently developed, and in 1962, a patent for this innovative pressure containment concept was granted to Baltzar Von Platen at ASEA.

In the 1960s, a number of companies realized the potential of adopting the HIP process commercially for the improvement of powder components. Crucible Steel thoroughly investigated this application, and in 1967 installed their first production HIP, producing fully dense compacts of their high-speed tool steel. Meanwhile, Kennametal began a testing program for elimination of internal pits and flaws in sintered tungsten carbide preforms, and purchased their first HIP system in 1967.[2] Since then, HIP has been adopted by many companies for processing high performance components.

HIP Basics

Hot Isostatic Pressing is a forming and densification process using heated gas (most commonly argon or nitrogen) under very high pressure. Unlike mechanical force which compresses a workpiece from one or two sides, isostatic pressure is applied uniformly on all sides of an object, eliminating internal porosity without changing its net shape. The process can be used to treat preformed metal, ceramic or composite parts, and for compaction of containerized powder shapes. Maximum standard operating pressures can be specified from 1500 to 45,000 psi (10 to 207 MPa). Temperatures can range up to 2000°C. Higher pressures and temperatures can be provided for special applications.

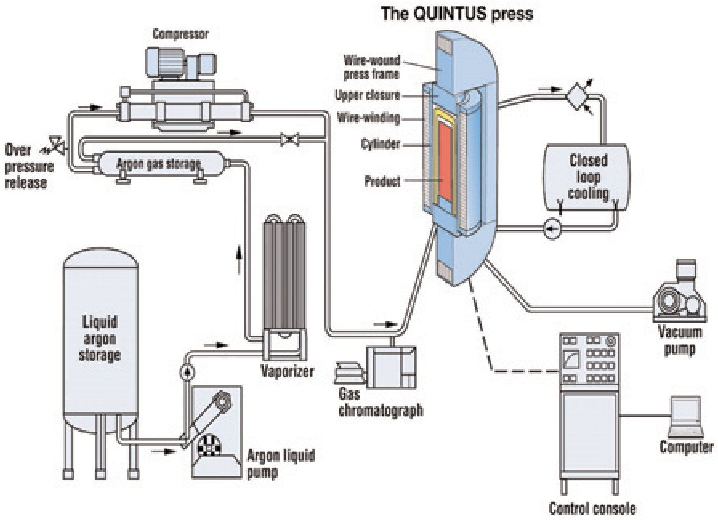


Figure 2.

Benefits of HIP

Over the years, HIP has proven its ability to significantly improve the physical properties of parts used in highly stressed applications, providing the following specific benefits:

Figure 3. Examples of near net shape parts produced from metal powder at Bodycote Powdermet AB

- Consolidation of castings and powder metal parts to 100 percent of theoretical density
- Elimination of internal defects and pores
- Improvement in mechanical properties. These include increased resistance to fatigue, impact, wear and abrasion, and improved ductility.
- HIP typically leads to more efficient production. Near net shape forming to precise tolerances means little or no secondary machining or manual rework and usually a better surface finish. The scatter band in measured properties is reduced, and scrap loss is decreased.

Applications

Currently, defect healing of castings is the largest market segment for HIP technology, but powder consolidation is on the increase.

Figure 4. Castings are routinely HIPped to remove internal porosity.

Densification of castings

The HIP process is widely used to improve the performance and durability of cast metal parts. Internal porosity is eliminated, and the HIPped castings typically have fatigue life and mechanical properties comparable to those of more costly wrought or forged products.

The most common uses for HIP densification are in the aerospace, medical, and power generation industries with high-performance metals such as titanium, nickel-based super alloys and stainless steels. Investment cast turbine blades, joint implants and engine components typically contain internal voids and flaws due to shrinkage during solidification. These defects are healed in the HIP process.

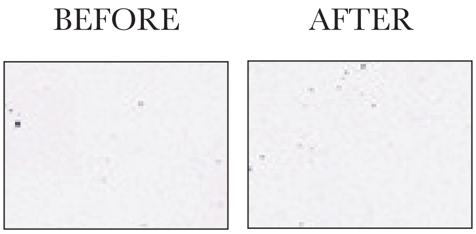


Figure 5. Microstructure of a nickel-based super alloy before and after HIP

The quest for lighter, more fuel efficient vehicles has resulted in the growing use of cast aluminum alloy components in the automotive industry. The first application of HIP technology in this arena was for racing engine components, and today has expanded into the high-performance commercial automotive market. The advent of larger, faster presses and lower-cost

Figure 6. HIPped cylinder head (photo courtesy of Eck Industries, Inc.)

purpose-built equipment has enabled contract processors such as Howmet and Bodycote to provide cost efficient casting densification for car makers and their suppliers.

For example, the special press built for Bodycote's Densal® process features a short five-hour cycle, a significantly larger work zone, and an annual pressing capacity of 6,000 tons of parts. Factoring in the lower purchase price for this customized press, total processing cost reductions can approach 90 percent compared to earlier HIP technology.[3]

Powder metallurgy

HIP consolidation of PM parts is becoming an increasingly viable alternative to the long lead times and high cost of forgings, and has unique advantages over conventional methods:[4]

Figure 7. Valve body for offshore application in high alloy austenitic and duplex steels (photo courtesy of Metso Powdermet AB)

Figure 8. Dipole cryomagnet end cover HIPped from 316LN stainless steel powder operates in cryogenic environment of -268°C (-450°F). (photo courtesy of Bodycote HIP-Surahammer)

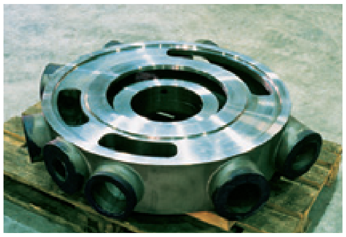


Figure 9. 12% Cr steam turbine chested near net shape formed by PM-HIP

Figure 10. Fully densified cemented carbide rolls and wear parts

- Fully dense parts with homogenous structures leading to isotropic properties and freedom of shaping
- Clean processing with encapsulated powders
- Near or net shape design flexibility with short series economy
- Consolidation and sintering carried out simultaneously. With advanced furnaces, solution treatingcan also be accomplished.
- Ability to process a large number of parts of varying shapes and sizes in a single cycle
- Exceptional dimensional stability and grindability
- Compound or clad products with optimized material properties

Two basic HIP methods are employed to compact powder parts:

Direct HIP involves gas atomized powders of less than ~92% density that are placed in a gas-impermeable metal or glass container for consolidation, isolating the powder from the process gas. After fabrication and leak testing, the container is filled with powder via a fill stem while evacuating and heating. The stem is sealed and the contained powder is ready for HIP consolidation. Applications include tool steel manufacturing, near net shape components for offshore oil and gas equipment, steam turbines[5] and many other products. Tool steel and other alloy powder billets are HIPped and used as pre-forms for further processing such as extrusion.

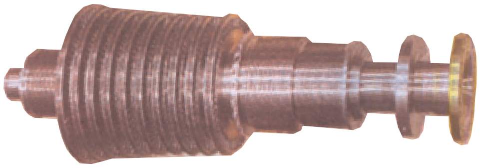


Figure 11. 650 kg Steam Turbine Rotor produced by direct HIP of stainless steel powders into near net shapes (Photo courtesy of Alstom Power Sweden)

Post HIP eliminates containerization by pre-compaction of the powder and sintering to 92% density or greater, then HIP. Pre-compaction methods include injection molding, slip casting, cold isostatic pressing or uniaxial pressing. Pre-compacts are typically rough machined, sintered, HIPped and final machined. Post HIP can be applied to a variety of powders, but may be best suited for materials with higher melting points such as carbides and ceramics.

Sputtering Targets

Targets are made from high-purity metal and ceramic powders, and are used in thin film deposition on products ranging from architectural glass to integrated circuits to flat panel displays. Hot isostatic pressing consolidates these costly containerized powders to homogenous, 100 percent dense structures with no segregation effects or loss of the required purity. In some cases, HIP is also employed to achieve a secure bond between the target and a cooling backing plate.[3]

Figure 12. Many targets benefit from HIP's ability to provide dense, homogenous structures with no loss of purity. (Photo courtesy of Material Science International, Inc.)

Diamond Cutting Tools

Figure 13. HIPped diamond beads

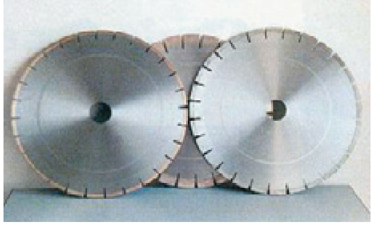


Figure 14. HIPped cutting wheel segments

In recent years, HIP has become an increasingly popular technique in the manufacture of diamond beads for wire sawing and diamond segments for cutting wheels. Hot isostatic pressing has proven to be a highly efficient method of consolidating the metal matrix with impregnated diamonds, offering major advantages over uniaxial sintering presses which have traditionally been used. These include dramatically higher throughput, compaction to 100 percent theoretical density, uniform diamond distribution with reduced pullout, improved hardness, and lower grain growth and graphitization at the diamond surface.

Diffusion Bonding (HIP Cladding)

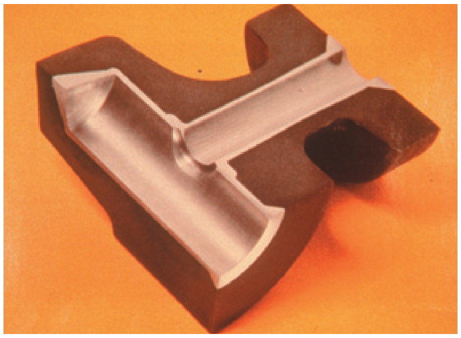


Figure 15. Corrosion-resistant alloy inner liner diffusion bonded to valve body

The original HIP developed at Battelle Labs was commissioned by the Atomic Energy Commission to bond the elements of nuclear fuel elements. Today, diffusion bonding remains a common application for HIP of high-performance components. Metallurgically bonded metal parts are created by cladding a layer of corrosion- or wear-resistant alloy to the substrate of a bi-metal component. Thick or thin layers can be applied, and high-cost materials can be conserved by using them only in selected, high-wear locations. Powder alloys are typically clad to solid metals, but solid-to-solid bonding is sometimes economically feasible.

Advanced Ceramics

Figure 16. Hybrid bearings with HIPped silicon nitride balls significantly outlast conventional bearings. (Photo courtesy of Norton/St. Gobain)

Figure 17. HIPped advanced ceramic materials are replacing metals in a growing number of critical applications. (Photo courtesy of Norton/St. Gobain)

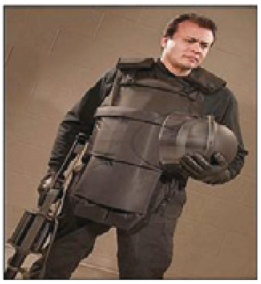


Figure 18. HIP adds toughness to ceramic body armor.

HIP has long been employed to densify engineered ceramic products such as silicon nitride ball bearings and thread guides, boron nitride injection nozzles and control rod pins, insulators, electrodes and pump components for the chemical industry. Ceramics can be both glass-encapsulated or post-HIPped.

Many new applications for HIPped ceramics have emerged, including:

- Ballistic protective glass, using Spinel and ALON
- Composite joint prosthetics, combining metal stems with sintered and HIPped powdered ceramic socket balls
- Body armor for military and law enforcement personnel
- Zirconia and alumina dental implants

Metal Injection Molding (MIM)

This is a growing technology for producing small, high-volume ferrous or non-ferrous powder metal and alloy products. MIM parts are typically 95 to 98 percent dense and can be molded in a variety of complex shapes. Parts tend to be small (in the area of 50 grams), and thus can be economically HIPped to 100 percent density by lower cost presses such as the Avure MiniHIPper®.

Higher Efficiencies

"Giga-HIPs"

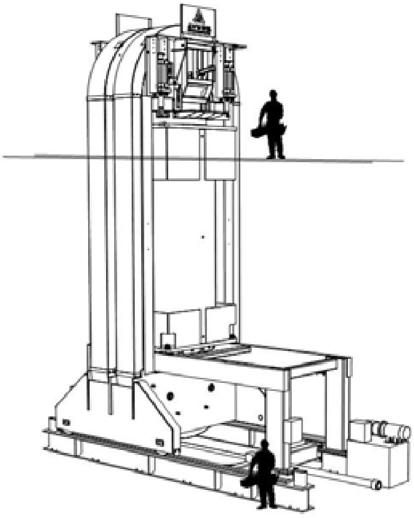


Figure 19. The world's largest hot isostatic press, now being built at Avure Technologies AB

An obvious way to lower unit costs of processed parts is to process more parts per cycle. HIPs are getting bigger, and the largest of all has recently been ordered from Avure Technologies AB, Vasteras, Sweden by Kinzoku Giken Co. Ltd., a Japan-based contract processor. Scheduled for installation in 2009 at the company's Himeji factory, this giant press will stand over 41 feet (12.5 m) and weigh more than 600 U.S. tons. The voluminous work zone measures 79 inches in diameter and almost 14 feet in height (2 x 4.27 m).

Bodycote, Surahammar, Sweden, will soon be operating a HIP with a furnace area measuring 71 inches in diameter and 10.8 feet high (1.8 x 3.3 m), the latest of several large presses installed by the company worldwide. Howmet Castings, Whitehall, Michigan, also has several large HIPs including a recently ordered 42 inch x 65 inch high model (1.07 x 1.65 m).

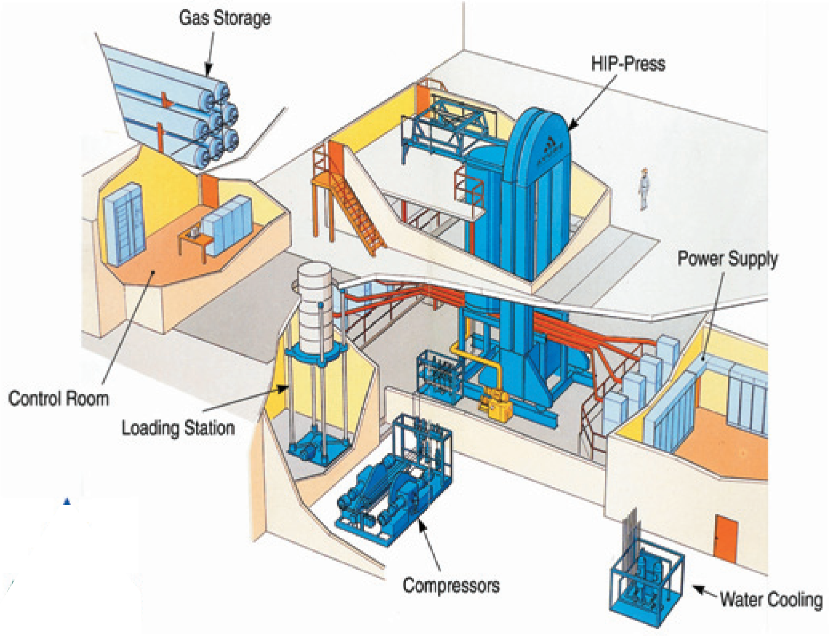


Figure 20. Complete HIP system in operation since 1987 at Bodycote in Surahammer, Sweden

High-capacity HIPs have the additional advantage of being able to process very large parts. Designers can create complex, single-piece castings that can now be HIPped intact, eliminating the need for fasteners or welds. The aerospace industry is already using HIP for large airframe sections and engine casings.

Faster cycling

Depending on the characteristics and sensitivity of the materials being processed, previous HIP cycles have taken as long as 24 hours. Great strides have been made to reduce this time to as little as 5 hours, which again lowers the per-unit cost of processed parts. This cycle reduction is possible by increasing the press's designed heating and cooling rates, while also reducing the process soak time whenever justified by previous experience and results.

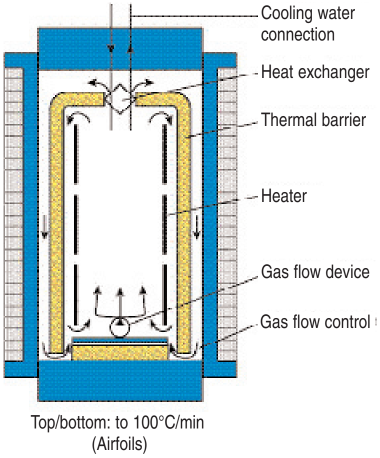


Figure 21a. Uniform Rapid Cooling (URC) furnace

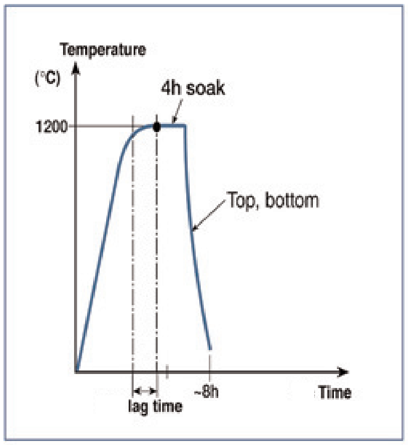


Figure 21b. Cycle curve using the URC feature, Hold times in many applications can be significantly shorter.

Many HIP presses can be equipped with advanced rapid cooling furnaces which have in some cases cut total cycle time in half or more. In some applications, such as small aluminum castings, times have decreased to a mere 2 hours. A programmable variable speed fan circulates cooler gas uniformly throughout the work zone. The cooling rate can be precisely controlled to avoid cracking in thermally sensitive ceramic parts. This feature not only reduces cycle time, but also adds the possibility of combining the HIP process with solution heat treating for metal alloys.

Figure 22. Cycle parameters can be entered and displayed on the system computer.

Advanced process control

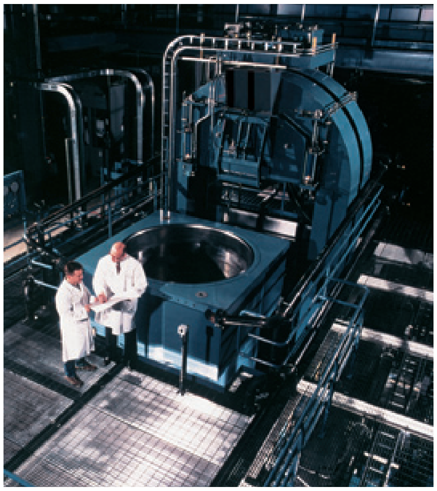
In the last decade, significant improvements have been made in the computer control systems used to regulate the HIP cycle. These systems offer far more precise temperature control, and more uniform heating throughout the multiple zones used in the newer HIP furnaces. This results in higher throughput of quality parts and reduced scrap loss. There is also less temperature fluctuation around setpoint, which avoids the wasteful entry and venting of process gas when the signal is "bouncing".

Press Configurations

HIPs are available in two basic size categories:

1. Laboratory/Limited Production Scale. These are small, compact presses often housed in a single module for HIP research and prototyping studies. Work zone dimensions range from 3” dia. x 5” high (.076 x .126m) to 10” dia. x 30” high (.255 x .762m). The larger of these units are also being used in pilot plants and for small batch/small part production.

2. Production Scale. Larger HIPs process higher volumes and are typically integrated into a plant’s manufacturing system. About half of these units currently in operation are owned by contract service facilities, or “toll HIPpers”. Work zones extend from 12” dia. x 35” high (.305 x .891m) to the world’s largest HIP now being constructed (see page 7) which will measure 79” dia. x 14 ft. high (2 x 4.27m).



Safety Considerations

The gas pressing fluid in the HIP process has a far greater compressibility than water, and therefore substantually increases the internal energy within a pressure vessel. This energy must be contained safely and reliably throughout the entire design fatigue life of the vessel. Monoblock vessels are used in some HIPs, but pre-stressed and wire wound vessels and yoke frames are widely acknowledged to be the safest pressure containment systems ever designed. The yoke frame holds the threadless vessel end closures in place, eliminating stress concentrations and tensile loads in the body.

The wire wound system is designed to cool the vessel internally to minimize thermal stresses in the vessel wall, which is particularly important when rapid cooling furnaces are selected. This internal cooling feature

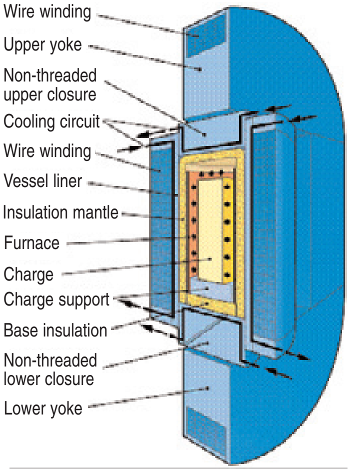


Figure 23. Wire wound vessel and yoke frame

helps the vessel to meet the "leak-rather-than-break" criteria. Wire wound HIP systems can be calculated and built for an almost infinite fatigue life, and are typically constructed for 20,000 to 30,000 cycles, which is usually far longer than the technical service life of the system as a whole.

Modern computer control systems also contribute to operational safety with built-in interlocks, alarms to signal any abnormalities in the pressure cycle, and automatic shut downs when warranted.

A promising future

The trend toward bigger, more cost efficients HIP systems is continuing, even accelerating. The technology already exists to construct presses more than double the size of the largest units now in production. These gigantic capacities, coupled with shorter cycle times, will fundamentally change the way many products are designed and manufactured.

Large sub-assemblies consisting of multiple HIPped components may soon be able to be processed as a single cast or molded unit, eliminating many secondary operations while enhancing overall performance integrity. Commonly HIPped items can be made much larger, thereby increasing the size and operating efficiency of end products such as jet engines, gas compressors, and power generation equipment. The batch size of smaller parts can increase exponentially, dramatically lowering the per-unit cost of HIP.

Conclusion

Hot Isostatic Pressing has long been an essential process in the production of high-performance cast and PM parts for critical applications. Thanks to the recent development of higher capacities, shorter cycles, and precise control systems, HIP today is significantly more cost-effective, and will be even more so in the future. As a result, this proven technique is becoming economically justifiable to a growing number of manufacturers, and innovative new applications are continually being tested and adopted.

AVURE TECHNOLOGIES

www.avure.com

Avure Technologies, Inc.
22408 66th Avenue South
Kent, WA 98032 U.S.A.
Phone: +1 800 610 1798
Fax: +1 253 981 6350

Avure Technologies, Inc.
3721 Corporate Drive
Columbus, OH 43231 U.S.A.
Phone: +1 614 891 2732
Fax: +1 614 891 4568

Avure Technologies AB
Quintusvagen 2
SE 72166
Vasteras, Sweden
Phone: +46 21 327000
Fax: +46 21 141817

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