Challenges and New Solutions for Production of Complex Shaped Parts from Ti Alloys via PM HIP.

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Abstract
In the recent past there were several reasons for PM HIP of shaped Ti parts were not extensively used:

- Very high cost of powders and processing
- Coarse powders (potential inclusions in as HIPed condition);
- Mechanical properties;
- Purity issues (Inclusions)
- Oxygen pick up;
- Non-destructive inspection;
- Dimensional precision;
- Not enough technical expertise

Presently the situation has changed radically mainly due to the new technologies introduced enabling a much wider use of PM HIP:

- Reduced cost of powders and processing
- Finer powders
- No porosity and PPB concerns
- Properties same or higher that wrought
- No oxygen pick up
- Better UT inspect ability
- Better machinability
- Exceptional technical expertise

The near net shape PM process enables to develop and produce economically various types of the complex shape parts and also provides the design enhancement due to the combination of “as cast” complex geometry as well as the properties of HIPed powder exceeding those of the wrought material

Introduction
HIP (Hot Isostatic Pressing) is efficiently used in PM (Powder Metal) as a consolidation technique for large size billets from many advanced powder compositions. However, the advantages of HIP can be revealed by introducing its shaping potential through manufacturing complex, “near net shape” parts which will have both the shape complexity of castings and the properties of wrought material.

During the last decade of HIP, this “net” and “near net shape” approach was extensively developed for aerospace needs. Numerous applications utilizing large size, critically loaded components require improvement of cast properties or cost reduction for forged and milled products. New advances in HIP tooling design and manufacturing
techniques have enabled the transfer of HIP from an elaborate process to a production technology for a wide spectrum of materials from light to heavy metals.

The main technological tools described are:

- process modeling accounting for the substantial deformation of powder and HIP tooling during HIP
- tooling design and selection of appropriate tooling materials
- advanced tooling manufacturing for sacrificial and reusable tooling elements
- novel non destructive procedures adapted for complex shape parts

The major applications of this process are many Energy / Oil and Gas industry, Process industry, Science and Aerospace industries. EPMA slide

**HIP of Complex Shape Parts**

Hot Isostatic Pressing (HIP) of powder materials is widely used in industry for production of critical components with high-level properties requirements. However, most of the products produced by HIP are rather simple shape blanks requiring substantial post process machining to achieve final shape and dimensional tolerances. Small production lots for large size components, using parts configured to “near net shape” with sacrificial tooling made from cheap low grade steels, filled with powder, and HIPed have shown affordability when compared to investment casting or machining from blanks. The ability to manufacture with “net shape” and “net surface” provides lower cost, shorter development cycle, and reduces the design limitations of traditional manufacturing techniques. The capability to fabricate complex, monolithic shapes without welding provides enhanced service life for critical components in addition to the fabrication and inspection cost savings.

**General Tasks for the development of PM HIPed complex Shape Parts**

Due to the substantial shrinkage during HIP process, the advancement towards “net shape” HIP is enabled by elaborate process modeling. The steps to highly desirable “net shape” products are improvements to process models used to design HIP tooling. The more advanced modeling accounts for plastic and creep deformation of compressible powder media interacting with solid HIP tooling as well as the evolution of material properties during HIP cycles. The final benefit is to reduce the need for time-consuming and costly experimental iterations by employment of more accurate first-time-through process modeling.
Currently, critical applications within the industry have continually brought examples of the technological compromise between performance characteristics and cost that is very often closely related to dimensional precision. This compromise is the reason for the pursuit of an alternative to the two basic technological processes of manufacturing complex shape parts: investment casting and forging + machining.

The Hot Isostatic Process makes it possible to combine dimensional precision typical for cast parts with the properties of a forged material while gaining improved homogeneity of the microstructure. This can be a potential winner in this competition if the problem of shape control during HIP is solved. This is one of the most complicated technological issues because the final “as HIP” geometry of any part is a result of non-uniform shrinkage of more or less isotropic powder bulk placed in a complex shape metal capsule.

HIP provides a uniform microstructure and properties, regardless of size and shape, which can be extremely efficient and important for the development of large size, complex shape parts. For example, the new generation of highly powered jet and rocket engines has critically loaded components that can reach up to 1000 lbs in weight and 50” in diameter. Very often, PM HIP is the only technology providing the necessary combination of cost and performance. The potential applications are both static and rotating components, such as impellers, turbine and pump wheels, housings, manifolds and jackets, all made from existing advanced high strength and environmentally compatible powder alloys. The only way to economically manufacture these components from advanced powder alloys is to produce them with selectively net shape, avoiding welds and machining of intricate internal surfaces.

Selectively Net Shape Hot Isostatic Pressing (SNS HIP) is based on the computer modeling of tooling using existing computer aided design systems (CAD) that would, when combined with powder, result in a “net shape” part per drawing requirements. This process can be directly applicable to static and rotating parts and the large structures made from high strength and environmentally compatible Nickel and Titanium alloys.

Modeling of the deformation during Hot Isostatic Pressing is essentially important to be able to predict the initial dimensions for the HIP tooling to provide a selectively net shape after HIP.

This modeling is to a large degree complicated by the unknown properties of the material during its consolidation within a specific HIP cycle and combination of the
compressible (powder) and non-compressible (HIP capsule and inserts) material within a part.

(Figure 2).

The following 3 applications for rocket engines and missiles based on the SNS HIP will be analyzed below:
- Shrouded SNS impellers for the turbo-pumps of rocket engines;
- Thin walled jackets supporting the combustion chambers
- Thin-walled complex shape structures of the missiles

**Shrouded Ti impellers for the turbo-pumps of rocket engines**

Selectively Net Shape HIP enable to manufacture turbo-pump impellers for upper stage rocket engines of the advanced aggressive designs, free from machining and forging limitations from the high strength Ti alloys capable of operation at cryogenic –423F temperature.

Figure 3 illustrates the general steps in development of PM Impellers based on HIP modeling: design, computer modeling of deformations during HIP, manufacturing of HIP tooling and HIP itself.
After the modeling, computer simulations and design of the HIP tooling are complete, the following technological steps are needed to produce the PM selectively net shape impellers:

- Manufacturing of the tooling;
- Cleaning, assembling, welding, inspection of the HIP tooling
- Filling the HIP tooling with powder, hot out-gassing, sealing;
- HIP;
- Pre-machining for UT inspection and UT inspection
- Acid leaching of the mild steel tooling
- Dimensional inspection, re-modeling and design of the second iteration HIP tooling.
Figure 7. Cost comparison for PM HIPed and machined impellers for rocket engines. As a result, the insert comes out of a precise shape (3-5 thousand of an inch tolerance) and optimal surface finish of about 32 RMS. Figures 8 and 9 show these inserts for the two geometries of impellers.

Figure 8. CNC Machined Insert for Aerojet Impeller

Figure 9. CNC Machined Insert for Northrop-Grumman Impeller
Assembling of the capsules with the inserts for filling is done in the “clean room” 10,000 conditions using the appropriate attire of the personnel to avoid external contamination of the capsules. Figure 10 illustrates the steps if this assembling.

Figure 10. Clean Room Assembling of the HIP tooling for a rocket engine Impeller

Welding of the assembled capsules is also done in the clean conditions of the Ar-glove box providing the reduced concentration of oxygen inside the capsule and enabling to avoid the oxidation of the inserts.

The final operations with the HIPed impellers include:
- Pre-machining;
- UT inspection;
- Acid leaching and chem.-milling
- CMM dimensional inspection

After HIP the outer contour of the impellers is machined to a sonic shape
- to bare the HIP, tooling (inserts) covered by the capsule and powder to provide access for acid for its efficient removal;
- To provide a novel UT inspection technique of the external “sonic” geometry with the complex shape low carbon steel tooling in.

Figure 11 shows an impeller after pre-machining and prior to ultra-sonic inspection.
The Figure clearly shows the ring material (Ti alloy) of the hub, shroud and vanes and low carbon steel surrounding it.

Figure 11. Rocket engine Impeller Pre-machined for UT Inspection and Acid Leaching

Special software has been developed to conduct ultrasonic inspection of the impellers with the low carbon steel HIP tooling being still on the part. This software can distinguish the signals from the Ti alloy from the response from the steel and indicate the defects (if any) in each of them (Figure 12). The advantage of this approach is that the net shape geometries can be inspected, while the inaccessible “dead areas” typical for UT inspection can be “hidden” inside the steel tooling.
The dark blue and black areas on the Figure 12 are the scans of the Ti alloy while yellow, red and green areas present the signals from low carbon steel tooling different in its acoustic characteristics. The presented scans demonstrate the excellent UT quality of the PM impellers with no detectable indications of the size more than 0.015” in the parts.

Acid leaching is done in nitric acid that does not attack the corrosion resistant Ti alloys at low temperatures, but completely dissolves the low carbon steels. During active leaching the temperature of the process can significantly increase and this may cause some surface damage of the impeller, therefore the temperature is controlled by slowing the process or active cooling of the circulated acid. On the other hand the chemistry of the bath is altered to avoid electro-chemical passivation and formation of non-dissolvable small “freckles”, Figure 13.
Acid leaching of SNS tooling

Figure 13. Acid leaching of HIP tooling off the Ti impellers

This enables to fully remove the steel from the narrow and hardly accessible channels of the impellers. The final operation of chem-milling is aimed at removing of 0.002-0.003" from the surface to improve the finish and remove the diffusion layer of this thickness that is enriched by carbon and iron due to their diffusion into Ti alloy during HIP from the capsule material.

Detailed dimensional inspection of the manufactured impellers is important to verify the accuracy of the models used and the capability of the process itself and is done using various CMM tools (Figure 14).
Figure 14. CMM of the inlet of the impeller

Figure 17 presents the assembly of the USET impellers manufactured via SNS PM HIP from advanced Ti alloys.

Figure 17. A set of Ti impellers for the upper stage rocket engines

Net and Near Net Shape HIP For Complex Shape PM Parts from Ti alloys

The manufacturing of large, complex geometry HIPed parts from powders of Nickel and Iron based super alloys and Ti alloys requires tooling designed from computer
programs with embedded engineering models of powder consolidation and shrinkage that use the Computer Aided Design (CAD) model of the desired part. The Powder Metal – HIP process based on modeling has brought the opportunity to have investment cast dimensional precision with material properties closer to forging and machined properties. The desire to use this (parts from powder) approach is largely due to the ability to reproduce investment cast configurations, often with better dimensional control, that have improved material properties which result from homogeneous microstructure.

Though this tooling is sacrificial, for small production lots, the HIP process has been shown to be cost effective when compared to investment castings or machining from raw material blanks. The cost of tooling capsules made from cheap low grade steels is much less than that of the high performance material to be machined off a blank to provide a net shape part. Additionally, the investment casting tooling costs are not efficient at low production quantities.

Figures 18 and 19 show the development and processing steps of the current selectively net shape technology for as HIPed powder metal structural casing from a high strength Ni-base super alloy.

![Figure 18 Conceptual tooling design and FEM modeling for thin walled housing from Ti-base alloys.](image-url)
These parts can be made with the net shape (especially for internal channels) or with the near net shape enabling final precise machining, but the major concept of HIP remains the same: conceptual HIP tooling design, HIP Modeling and manufacturing of the HIP tooling so that eventually the final part comes out cost efficient compared to the machining from a simple forging.

Figures 20-23 illustrate the manufacturing process for such parts including HIP, acid leaching and CMM analysis showing the precision of the near net shape approach.

Figure 20. HIP capsule of Titanium Jacket prior to HIP
Figure 21. Titanium HIPed Jacket after acid leaching

Figure 22. CMM of the near net shape Jacket
Figure 23. Results of the dimension an analysis for the PM Titanium Jacket

Thin-walled structural shells of the missiles

Some of the missile components operate at high temperature and stresses and require manufacturing from the advanced Ti or Ni-base alloys. Combined with very complex shapes and usually thin walls they become extremely difficult and even challenging for manufacturing technologies. Figure 29 presents an example of such a component. Operation temperature, weight and stress conditions required the use of high strength Ti 6-2-4-6 alloy.
Machining of such an entirely 3-dimensional thin-walled, 0.060” thick configuration with internal flanges from a billet with the “buy to fly” ratio of 20:1 and more is economically unreal, investment casting usually does not provide enough strength and fatigue. Selectively Net shape PM HIP becomes then a viable approach providing a uniform and homogeneous micro-structure in the entire component along with the minimum of machining.

To avoid extremely expensive machining of the internal profile of the part is manufactured with the internal net shape using a low carbon steel mandrel that forms its precise internal contour (Figure 30) and thin external capsule with simplified shape providing the near net shape outside (accessible for machining) with about 0.050” extra thickness to be finally machined of.
Figure 30 HIP tooling concept for the thin walled SNS PM HIPed parts

Within this concept, machining of the tooling is relatively simple and can be easily inspected, Figure 31.

Figure 32 presents the assembly of the HIP tooling prior to filling and HIP.

Due to the design of the HIP tooling consolidation and shrinkage of the powder occur almost uni-directionally, i.e. radially- that also enables much better dimensional control of the process.
Figure 31. CMM inspection of the HIP tooling

Figure 32. Assembly of the HIP tooling prior to filling and HIP
Figure 33 shows the capsule after HIP and Figure 34 - the final selectively net shape part after de-canning that was done by machining and acid leaching the remains of the mandrel.

Figure 33 HIPed capsule for the Ti 6-2-4-2 structural shell

Figure 34. Selectively net shape part after HIP
**Conclusions**

Various advances in HIP technique enable to extend the applications of this powerful technique in powder materials and diffusion bonding and to cost efficiently build complex shape highly stressed components for the harsh environment of rocket engines and missiles. Complex shape parts with dimensional precision of investment casting and structural properties of wrought material can be made by HIP using computer modeling and advanced design of the HIP tooling.
Challenges and New Solutions for Production of Complex Shape parts from Ti alloys via PM HIP

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• Process Modeling, accounting for the substantial deformation of powder and HIP tooling during HIP.
• Tooling Design and selection of appropriate tooling materials.
• Advanced tooling manufacturing for sacrificial and reusable tooling elements.
• Novel non destructive procedures adapted for complex shaped parts
Uses of the PM HIP: a world of possibilities

Energy / Oil and Gas Industry
- Swivel
- Wye-piece
- Impeller
- Valve Body
- Oil Riser Tube
- Turbine Rotor

Process Industry
- Grinding Roll
- Suction Roll Shell for Paper Machine

Transportation
- Injection Nozzle
- Rocket Impeller

Science
- CERN End Cover
- ITER Part Prototype

Tooling for metal, plastics & paper processing
- Gear Cutting Tool
- Broaches
- Screws for Plastics Extrusion
- Paper Slitting Blades
- Rolls

PM HIP Technology

Imagine new designs with Powder Metallurgy and Hot Isostatic Pressing

- Are you looking for solutions to reduce production and machining costs?
- Do you design metal parts with difficult-to-machine shapes or with complex internal cavities?
- Do you wish to reduce the number of welds and associated ultrasonic inspection?
- Do you wish to shorten your manufacturing cycle times?
- Are you looking for improved metal characteristics such as fine microstructure and isotropic properties?
- Are you looking for innovative solutions to produce small series of parts?

If you answer YES to one or several of these questions, the PM HIP technology is for you!

This leaflet is a publication of the EPHG, the PM HIP group of EPMA. For more information contact Jonathan Wroe at jw@epma.com
Examples of the net and near net shape PM HIPed parts

- Static and rotating components of the rocket engines
- Bimetallic parts with enhanced surface properties
- Compressors for off-shore applications
- Casings for jet engines
Shaping Tools for PM HIP Ti impellers

Before powder fill, degas & HIP:
Capsule & Insert tool

After HIP:
(1) Rough machine to remove capsule and produce UT
(2) Acid leach to remove insert
(3) Finish machine exterior surfaces
As-HIP’d Ti-6-4 Microstructure gives Higher Design Allowables

- More isotropic tensile properties of HIP’d P/M give higher minima than wrought or cast
- HIP’d P/M ductility & toughness significantly higher than wrought or cast
- Isotropic & consistent HIP-PM will allow a single material spec per alloy – not dependant on processing route

Smaller scatter-band

Covery Dr. Wayne Voice, Rolls-Royce, UK
Selectively Net-Shape Powder Metal Processing

Provides Cost, Performance & Life Benefits

Ni-based superalloy, single-piece housing & nozzle after selective acid dissolution of tooling

Tooling Assembly

Selectively Net-Shape Powder Metal Processing

Provides Cost, Performance & Life Benefits

Single piece shrouded turbine blisk with net-shape blades – Fe-based superalloy

- Avoids welding, casting, forging and complex machining
- Provides uniform microstructures in very large components
Micro-structure of PREP “as HIPed” Ti 6-4 powder (-35 mesh)
HIP modeling for a rocket engine Ti Impeller
Synertech PM Inc.
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Ti impellers for the upper stage rocket engines (Ti 6-4, Ti-5-2.5)
Structural PM HIPed Housings and Casings (2)
HIP modeling for a rocket engine Ti Impeller
Acid leaching of SNS tooling

Technical goals:
- complete removal of SNS, no “freckles”;
- no surface attack on the alloy;
- surface quality acceptable for NDT;
Structural PM HIPed Housings and Casings (2)
Structural PM HIPed Housings and Casings (1)
Dimensional precision for Near Net shape components
Structural PM HIPed Housings and Casings (3)

Net weight- 6 lbs
As HIPed- 7 lbs
Blank for machining-140 lbs
CONCLUSIONS

Near Net Shape HIP of Ti alloys based on Modeling provides:

- Material affordability;
- Increase of material utilization for complex shapes;
- Properties as wrought or better, shape- as cast or better;
- Efficient Non-destructive inspection;
- Capability for re-design of critical components;