

“Net Shape HIP For Complex Shape PM Parts As A Cost-Efficient Industrial Technology”

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ABSTRACT

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 developed and used mainly for aerospace needs. However, numerous commercial applications in power generation, gas and oil industry and other areas 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 elaborate aerospace process to an industrial technology for a wide spectrum of materials from light to heavy metals.

INTRODUCTION

The main technological tools described in the following document 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
- efficient decanning technologies

Various examples of commercial applications of “net shape” HIP are presented and discussed. Some of these examples are turbine wheels for power generation, impellers for oil industry and large components for aerospace applications.

Hot Isostatic Pressing (HIP) of powder materials is widely used in industry for production of critical components where high-level properties are required. 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 HIP’d 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.

The advancement towards “net shape” HIP is enabled by process modeling research and development. 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 454 kg (1000 lbs) in weight and 1270 mm (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.

Some examples include: 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 Designs (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 Iron based Superalloys, as well as, Titanium alloys.

There are four basic technological tools within HIP technology that enable us to solve the problem of “net shape” manufacturing. These tools also supply a developmental effort, which is a reliable and reproducible manufacturing of a complex shape part by HIP. They are:

- 1) Adequate process modeling that enables us to describe and optimize the flow pattern.

- 2) Optimal HIP tooling design, which helps to eliminate distortions and to minimize the influence of stochastic factors.
- 3) Experimental step through an informative demonstrator revealing the details of the deformation, map which could not be predicted within the model of the process while supplying necessary additional information and
- 4) Iterative information loop based on the computer analysis of dimensional data files, starting with the specification of the part through modeling and capsule design to “as HIP” geometry.

Consistent use of these tools provides the possibility of decreasing the development period by 4-6 months. These tools also offer efficient manufacturing of complex shaped engine parts.

New solutions to these problems can be revealed in the field of advanced mathematical modeling of HIP shrinkage accounting. This is evident through the actual 2D and 3D geometry, showing boundary conditions at the powder-tooling interface, inherent anisotropy of pores evolution and very special rheology of the processed media consisting partially of compressible (powder) and non-compressible (inserts) materials. These solutions far surpass the traditional concept of a HIP capsule as just a can transferring isostatic pressure to the powder and providing its 100% density. The capsule for a complex shape part appears as a plastically deformed special technological shaping tool.

It is also important to keep in mind that the stochastic characters of most technological parameters involved are of non-negligible influence on the shrinkage. Due to this influence, it is practically impossible to ensure “net shape” geometry of the entire part, inclusive of its internal surfaces. Today’s level of computer modeling and CAD open the possibilities for efficient control of the shrinkage and stable manufacturing of parts with critical “net” surfaces.

Shrinkage of powder material during HIP occurs due to the following mechanisms of deformation: plasticity, creep and diffusion. Strict accounting of these mechanisms is an extremely complicated task, and one should determine rheological characteristics of material. It has been proven that an adequate description of shrinkage for typical HIP cycles may be done on the basis of plasticity theory applied to powder materials [1,2,3].

The main distortion of powder placed in steel capsules takes place on the first stage of densification, during the plastic deformation of powder. Further densification goes on under constantly growing pressure. Meanwhile, the powder is at a limited (yield stress-strained) state.

Only in the final (dwell) stage of densification, when the main densification is over, do the mechanisms of high temperature deformation start working. The task of simulation of the shrinkage regularities can be reduced to the solution of a system of plasticity theory equations. These theories include: equilibrium equations, cinematic equations for deformation rate components, discontinuity equation, determination equations, thermal conductivity equations and Green's plasticity criterion.

For example (Green's plasticity criterion):

$$\frac{T^2}{f_1^2} + \frac{\sigma_0^2}{f_2^2} = \tau_s^2$$

, where f_1 and f_2 - some functions accounting the effect of average stress σ_0 and stress intensity factor T on densification and function of yield strength τ_s versus density.

In the case of plastic flow of incompressible capsule material the continuity hypothesis turns into an incompressibility equation.

Solutions of the closed equation set enable us to describe shrinkage of a powder work piece in a metal capsule, defining cinematic characteristics, stress-strain state parameters and distribution of density in the powder volume. An adherence law is assumed on the contact surface between powder and capsule.

The Finite Element technique is the computational method used in the software developed [2]. The area of application and validity is 2D axysimmetric and 3D parts with complex geometry.

The main problem, which determines the adequacy and effectiveness of the model of HIP, is data base creation for powder materials. For creating such data base, f_1 and f_2 functions from the main equations and plasticity criterion are necessary.

These functions determine the average stress and density relationship and sheer stress influence on the densification. It is obvious however, that the temperature factor is important and should be included directly or indirectly into the equations.

Experiments to identify f_1 and f_2 include interrupted HIP cycles and plastic deformation (upsetting at elevated temperatures) tests [4]. HIP tests are imitating regimes of a real technological process. The nest important item of the procedure is the definition of conditions of plastic deformation tests of the densified material. As the material is always in the limited stress-strained state during HIP, temperature conditions of the shear tests should be the same as they were during HIPing. Hot upsetting at corresponding temperatures is used for the plastic deformation tests.

As a result, the development process based on advanced modeling consists of the following steps:

- Generation of the file describing the geometry of an “as-HIP” piece;
- 2D modeling and development of the optimal capsule design;
- 3D modeling of densification and shrinkage during HIP and generation of the CAD file with the geometry of capsule and inserts forming the blades;
- Development of the software for NC milling or EDM;

- Manufacturing of the pilot set of tooling and HIP of the demonstrator;
- 3D measurements, computer processing, modeling and correction of the CAD file;
- Manufacturing of tooling and production of prototype part in accordance with specifications.

The manufacturing of large, complex geometry parts from “Hot Isostatically Pressed” (HIP) powder 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.

Forming during HIP is accomplished using tooling capsules, designed from the CAD model part, which provide the initial shape for the powder material and control the deformation pattern during its densification. Though this tooling is sacrificial, for small production lots (10 or less), which is typical for rocket engine components, the Powder Metal in a tool-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.

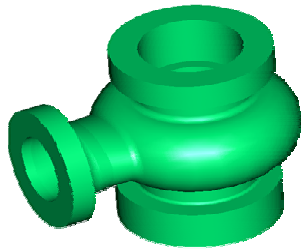
Figures 1 and 2 show the development and processing steps in Synertech P.M’s current technology as recently applied in a demonstration program with Boeing-Rocketdyne on a selectively-net-shape HIP powder metal turbine housing (IPD fuel turbopump).

Manufacturing Flow Chart at Synertech P/M



**Figure 1. Single – Piece Turbine Housing –
No Welds. No Castings. Low Cost Machining**

4 Months from a new design concept



Via process modeling,
tooling design,
manufacturing, and HIP



to a full-scale prototype

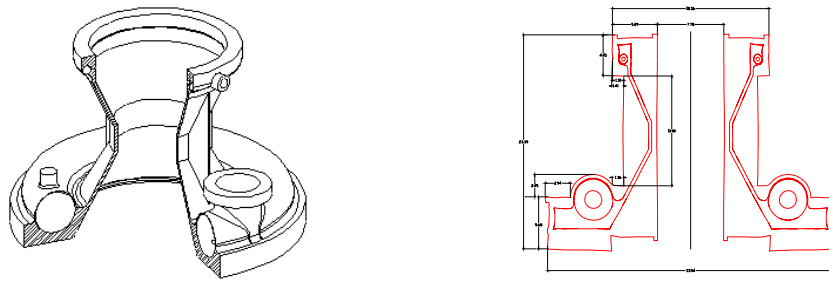


Figure 2. SNS HIP as Efficient Development Tool for Large Critical Components

Figures 3 and 4 illustrate different commercial applications in aircraft engines, power generation, gas and oil industry.



Figure 3. Impellers Present the Most Beneficial Applications for SNS HIP



Conceptual tooling design and FEM modeling

Figure 4. Development of Complex Net Shape Parts from Ni-base Superalloys

Conclusions

- SNS HIP Process provides material affordability even for expensive powders;
- The Process has been proven for Ni, Ti, Be- alloys, high strength steels, and Re alloys;
- The larger the size of the critical components,- the more benefits for SNS PM HIP;
- SNS HIP provides a capability for efficient re-design of critical components;
- The process is highly competitive for small and medium volumes.

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