HIP DENSIFICATION OF CASTINGS

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ABSTRACT

Hot isostatic pressing (HIP), a process involving the simultaneous application of heat and gas pressure, can be used to close internal porosity and improve the homogeneity of castings. Porosity and inhomogeneity can lead to lower yields and higher fabrication costs for parts made from castings and limit the application of castings because of lower strength and ductility than wrought materials.

HIP densification of castings has demonstrated the closure of porosity, reduced rejections from radiography and surface penetrant inspection, and improved weldability, chemical milling ability and mechanical properties.

Applications of the HIP process for castings have been achieved or are projected in four major areas:

- Lower cost castings by reduced X-ray and surface penetrant rejection
- Reduced component fabrication costs resulting from improved weldability
- Wider application of large, complex castings achievable by increased casting parameter latitudes possible when followed by densification
- Replacement of expensive wrought components with "premium" castings having increased fatigue strength and ductility.

HIP densification has been demonstrated on castings of many alloy systems ranging from aluminum and titanium to the superalloys. Densification parameters of temperature, pressure and time required for porosity closure have usually been determined empirically, although some theoretical predictions based on high temperature creep strength have been made. Densification of artificial porosity (drilled holes) is a useful study technique.

Surface bridging techniques have been developed to seal occasional surface connected porosity in order to provide the requisite impervious skin for closure of internal voids.

Scanning Electron Microscopy (SEM) techniques have been used to validate the metallurgical bonding achieved in closed porosity.

Introduction

This paper describes the use of hot isostatic pressing (HIP) to close porosity and improve homogeneity in cast alloys. Improvements are documented for Rene' 80, Ti 6Al-4V, Inconel 718 and 17-4PH alloys, encompassing mechanical properties, weldability, and chemical milling operations. It is projected that utilization of the HIP densification process will have dramatic effects on cost reduction as a result of higher casting yields, higher allowable design stresses, and improvements in the fabrication of components from castings which have been densified.

HIP Densification Equipment

The HIP densification equipment used for castings is relatively simple in that it uses only a cold wall pressure vessel with an internal furnace insulated from the pressure vessel walls. The castings to be densified are fixtured within the heated zone and subjected to an isostatic inert gas pressure. The arrangement is shown schematically in Figure 1. Typical process conditions are 1600 to 2200°F at a 10,000 to 15,000 psi gas pressure. A more detailed discussion of equipment as it relates to temperature and pressure control, surface contamination during processing, cycle times, etc., while important in the utilization of the process, is beyond the scope of this paper.

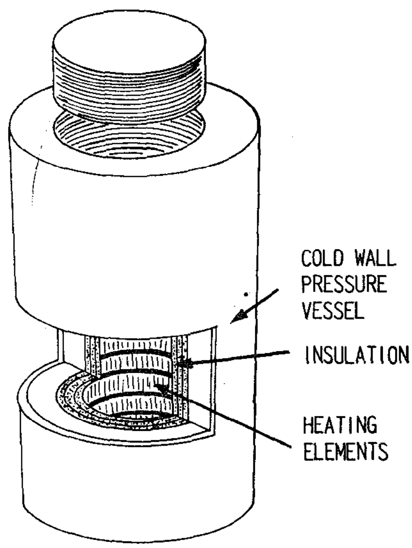


Figure 1. HIP Equipment Schematic.

Experimental HIP Study Techniques

The use of artificial porosity (drilled holes) can facilitate the study of closure mechanisms and parameters. An early effort was the HIP closure of artificially produced defects in wrought Inconel 718. Holes were drilled into the ends of several lengths of 1" square bar stock. Figure 2 shows the 1/32", 1/16", 1/8" and 1/4" holes in three bars which were HIP'ed later at 1825°F. Bars with 1/4" holes were also HIP'ed at 1925°F and 2025°F. An EB weld along the perimeter of the interface between the 1" square solid cover bar and the drilled bar provided the gas impermeable seal necessary for defect collapse.

EB welding in vacuum assured that no significant amount of internal gas would be present to prevent closure.

X-rays verified that only partial closure was achieved at 1825°F (Figure 3). More local metal movement occurred on the larger holes and at those holes near the surface. These two effects can be predicted from theory.

The 1/4" hole samples accurately reflect the tendency for defect healing at each of the three temperatures. At 1825°F the 1/4" hole was reduced to about a 1/8" diameter as shown in the X-ray. The 1/4" hole at 1925°F closed to about 1/16" diameter while retaining a circular shape. At 2025°F total closure occurred as evidenced by metallographic examination.

The position of a defect relative to the surface often determines the propensity for collapse during HIP. Holes near the surface and large interior holes are more likely to close than is a small interior defect. Thick wall cylinder stress equations may be used to approximate collapsing stresses on casting voids as is shown in Figure 4.

Although the HIP experiment did not involve elastic cylinders, the equations do explain the dependence of closure on defect size and location.

Two conclusions can be drawn from the pore surface stress equations:

1. As r_o becomes larger (the defect is more to the interior of the sample) the compressive tangential stress at the pore wall becomes smaller and eventually approaches twice the applied external pressure.
2. With very small defects (about the size of shrink porosity), r_i approaches 0 and the compressive tangential stress again becomes smaller and approaches twice the applied external pressure.

This second conclusion is especially pertinent to HIP of castings. Even with very thick sections and small voids, the hoop stress should never be less than twice the external pressure. Thus, very thick sections should not deter porosity closure. Because elastic conditions do not prevail at high temperatures and pressures, the equation is not strictly applicable and in this respect, the reasoning is not rigorous. However, the equation should be a good approximation, and it assists in the understanding of the HIP closure mechanism.

In this HIP experiment a 1/32" hole .18" from the surface exhibited a 25% reduction, whereas a 1/4" hole .32" from the surface was reduced by 50%. Applying the equation with P = 10,000 psi, the σ_t for the 1/32" hole is 20,100 psi and 23,000 psi for the 1/4" hole. Because of the gross approximations in the calculations, the absolute difference in the hoop stress is not significant; however, the exercise does show the reason for greater closure at the large hole.

Another effective study technique is the use of the scanning electron microscope (SEM) to determine metallurgical bonding in porosity closure. SEM analysis of tensile specimen fractures of Inconel 718 castings HIP'ed at 1925°F and 2025°F show pretest voids in the former material and a sound fracture in the latter. This SEM technique can be used as a quality control tool.

Pre-HIP Surface Sealing

To enable internal porosity closure, the porosity must not be connected to the external surfaces. Surface connected porosity allows internal and external pressures to equalize, thus eliminating the "squeeze" closure force. After evaluating many surface sealing systems, nickel plating and TIG welding have been determined to be the most effective surface sealing techniques for Rene' 80

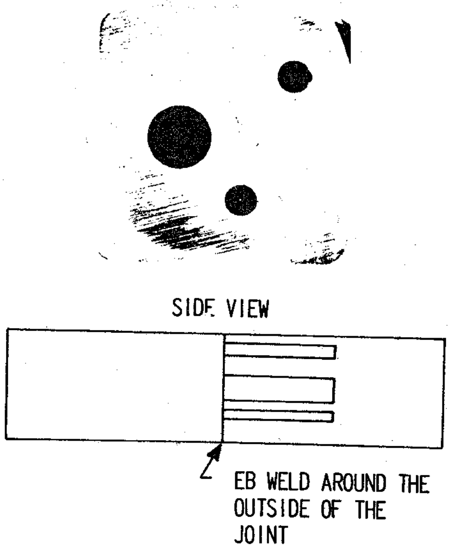


Figure 2. Preparation of Drilled Bar Specimens.

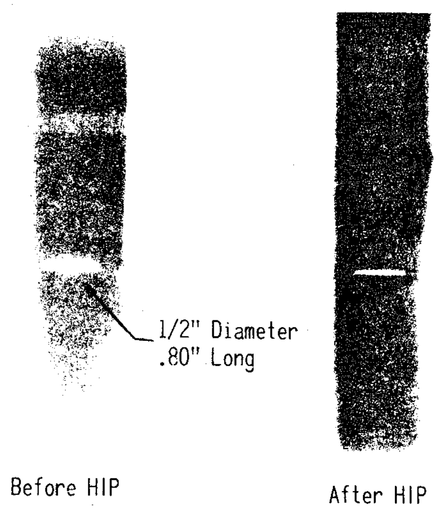
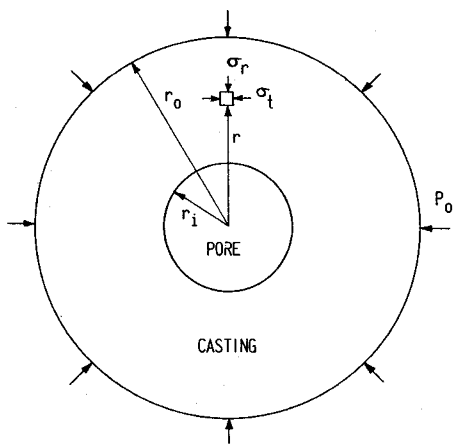


Figure 3 X-Rays Before and After 1825°F HIP



Equation A (Radial Stress): Equation B (Hoop Stress):

$$\sigma_r = \frac{-P_o r_o^2}{r_o^2 - r_i^2}\left(1 - \frac{r_i^2}{r^2}\right) \qquad \sigma_t = \frac{-P_o r_o^2}{r_o^2 - r_i^2}\left(1 + \frac{r_i^2}{r^2}\right)$$

for Pore surface where $r = r_i$:

$$\sigma_r = 0 \qquad \sigma_t = \frac{-2P_o r_o^2}{r_o^2 - r_i^2}$$

Figure 4. Thick Wall Cylinder Equations Application To HIP Densification.

and Ti 6Al-4V castings, respectively. From this study it was concluded that surface bridging should be reserved for situations with confirmed surface connected porosity. Nickel plating can add significantly to costs and also complications in removal after the HIP process. Surface chemistry alterations result from diffusion of the plating into the surface causing a nickel rich layer.

In general, it has been determined that proper casting parameters to provide a sound surface on the casting is the most effective technique.

Casting Porosity and Inhomogeneity Characteristics

Two basic, inherent characteristics occur to a lesser or greater degree in nearly all castings because of the nature of the solidification process. As most metals solidify, they shrink. Since heat extraction is through the mold walls, the outer surfaces solidify first which fixes the total casting volume. The inevitable solidification shrinkage must then occur in the last metal to solidify which is generally near the cross section centerline. Shrinkage porosity is controlled but usually not eliminated by the use of large volume gates and risers to provide heat and liquid metal sinks.

Compositional inhomogeneity upon solidification is another characteristic of castings. A simple binary solid solution phase diagram explains why the first metal to solidify is not only of different composition than the last to freeze but has a different freezing point.

The occurrence of shrinkage porosity and inhomogeneity in castings are undesirable both from a mechanical property and a fabricability standpoint, causing designers to compensate for lower properties. Densification of castings by HIP has demonstrated significant improvements in both characteristics. While there has been some optimism in the airframe and aircraft engine industries concerning the use of castings for large static structures, it appears that the industries remain reluctant to use castings for critically stressed large parts. Confidence in casting quality and mechanical property levels is justifiably low because of the wide spread in properties obtained from large castings as contrasted to forgings or wrought products. As a result, many designers use a "casting factor" which when applied, reduces the usable design strength properties of large castings approximately 25%.

Another factor is the Air Force directive (CP45B0002C Para. 3.3.16.6) which will not allow any material with less than 5% tensile ductility to be used as a support member for engine mounts. Currently, many castings have less than 5% ductility, thus prohibiting their use in large engine frames, in which engine mounting pads are provided.

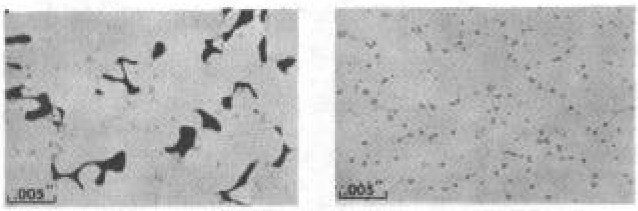
Responding directly to the above needs, General Electric conducted an Air Force program to establish HIP densification processes for Rene' 80 and Ti 6Al-4V on Contract F33615-75-C-1381, Process for High Integrity Castings. The program demonstrated that HIP successfully closes shrinkage porosity and improves the mechanical properties of these materials such that wider use can be made in jet engine manufacture.

Casting Densification Mechanism & Parameters

The mechanism of porosity closure by HIP involves creep and diffusion. Closure of casting shrinkage is really an ideal situation because the surfaces to be bonded are relatively clean. They are vacuum voids and may contain lower melting phases. The densification sequence is visualized as (1) mechanical closure by creep, (2) bonding and (3) homogenization by diffusion.

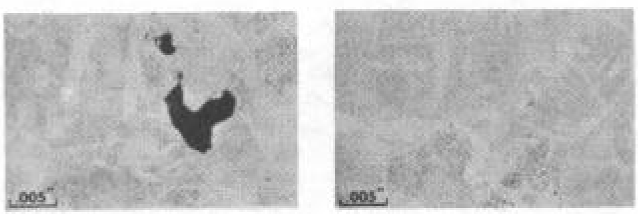
The Air Force program previously mentioned successfully established manufacturing processes for HIP densification of Rene' 80 and Ti 6Al-4V castings. The program dramatically demonstrated that shrinkage porosity is closed and metallurgically bonded in the densification process.

In Table I are listed the experimental HIP parameter runs that led to the production process choice of 2190°F/10 ksi/4 hours for Rene' 80. In Figure 5 as-cast porosity and HIP closure in Rene' 80 are illustrated. In the same study, titanium casting densification was demonstrated, as shown in Figure 6.



Porosity Prior To HIP　　　　After HIP

Figure 5. Microsections Of Rene' 80 Before And After HIP



Porosity Prior To HIP　　　　After HIP

Figure 6. Microsections Of Ti 6Al-4V Before And After HIP

TABLE I

Rene' 80 Experimental HIP Parameters

Temperature °F	Pressure ksi	Time Hrs	Porosity Closure
2225	15	2	Complete
2150	10	2	Incomplete
2150	15	2	80%
2190	10	4	Complete

Additional work had led to the establishment of HIP parameters for densification in other alloys. A representative list is shown in Table II.

TABLE II

Typical Densification Parameters

Alloy	Temperature °F	Pressure psi	Time Hours
Rene' 80	2190	10,000	4
Inconel 718	2125	15,000	3
Inconel 738	2175	15,000	3
17-4PH	1950	15,000	2
Inconel W	2175	15,000	3
Ti Alloys	1650	15,000	2
Al Alloys	950	15,000	2

Improved Mechanical Properties

Significant mechanical property improvements in Rene' 80 and Ti 6Al-4V were demonstrated on the Air Force program. Properties were measured on cast slabs in Phase I and actual components in Phase II.

Mechanical property improvements in Rene' 80 were demonstrated clearly for the Phase I slabs which contained gross porosity in the as-cast condition. These results are shown in Figure 7 in 1600°F high cycle fatigue. In Phase II, for test bars machined from the airfoils of the blades which contained little or no porosity, the results are as expected - little difference between non HIP'ed and HIP'ed material.

In Ti 6Al-4V, HIP densification substantially improved the fatigue life. Figure 8 for bracket castings shows runouts at 60 ksi maximum stress for 600°F high cycle fatigue vs 45 ksi for the as-cast condition. A substantial improvement in stress rupture properties via HIP in cast slabs is shown in Figure 9.

A significant effort has been expended in evaluating HIP densification of Inconel 718. Densification has made dramatic improvements in the mechanical properties of Inconel 718, especially tensile ductility. The data is shown in Figure 10. Densification eliminates porosity and improves homogeneity to assure high material integrity and ductility. All material received the following heat treatment after HIP:

2000°F 2 hours - air cool
1700°F 1 hour - quench
1325°F 8 hours - cool to 1150°F @ 100°F/hour
1150°F 8 hours - air cool

Low cycle fatigue testing Inconel 718 from 1/4" thick cast plates is presented in Figure 11. The non-HIP'ed material typifies average Inconel 718 properties while the HIP densified specimens fall significantly above the non-HIP'ed average curve.

HIP densification of Ti 6-2-4-2 castings also exhibited considerable improvement over as-cast material, as shown in Figure 12. The data compare very favorably with wrought properties.

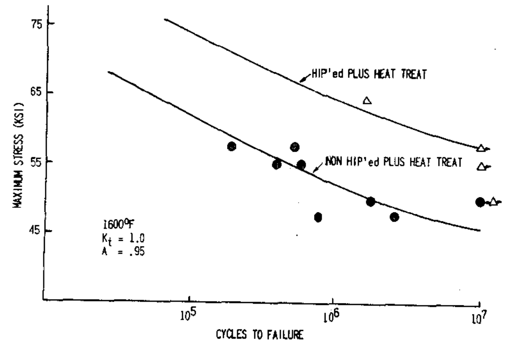


Figure 7. Rene' 80 High Cycle Fatigue Results - Cast Slabs.

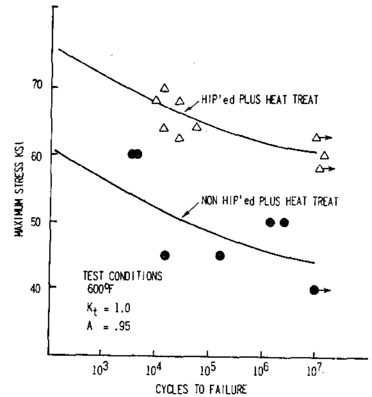


Figure 8. Ti 6Al-4V High Cycle Fatigue Tests - Mounting Bracket.

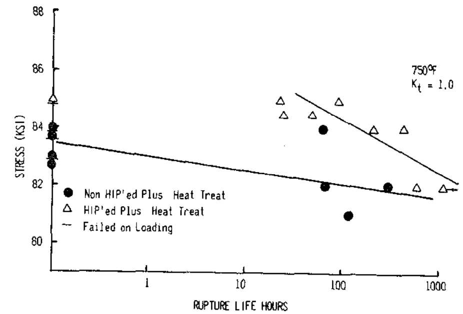


Figure 9. Ti 6Al-4V Stress Rupture Results - Phase I.

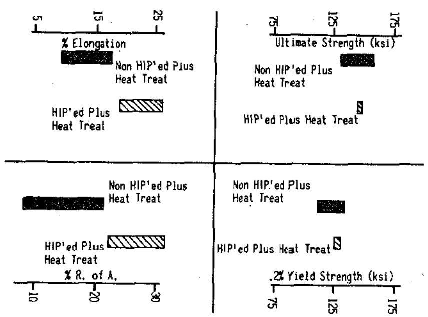


Figure 10. Cast Inconel 718 Properties.

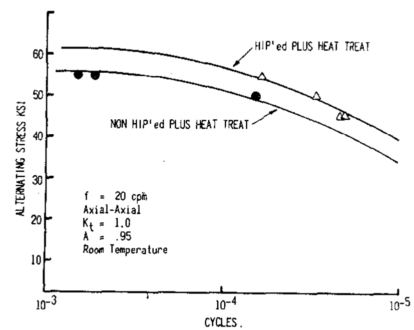


Figure 11. Inconel 718 Low Cycle Fatigue.

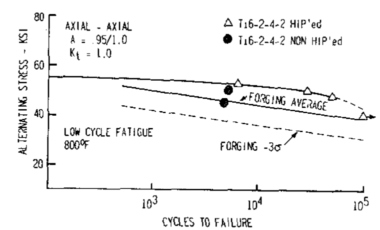


Figure 12. Ti6-2-4-2 Fatigue Properties.

Improved Weldability

Dramatic improvements in the weldability of cast Inconel 718 have been achieved by HIP where shrinkage porosity and inhomogeneity had caused weld cracking.

In initial manufacture, certain turbine frame strut end castings have exhibited numerous weld cracks in the heat affected zone at frame assembly. In the fabrication of the frame, weld repair of cracks, used to correct the condition, can be very costly and cause delays in the manufacturing cycle.

TIG welding on unrestrained strut end castings in both HIP and non-HIP'ed conditions, revealed that HIP substantially reduced the number of cracks. In an aggravated weldability test, as-cast strut ends exhibited an average of 15 and as many as 30 cracks per 5 inches of TIG weld bead. In addition, chemical cleaning prior to welding aggravated the non-HIP'ed cracking problem. In contrast, three strut end castings which had been HIP'ed and then chemically cleaned, were free from cracking after welding.

To isolate the individual effects of pressure and heat treatment, four as-received subassembly castings received a simulated HIP thermal cycle without pressure (2190°F/4 hours) in a vacuum furnace. Subsequently the castings were welded, producing considerable weld cracking (about 15 cracks per 5 inches), which demonstrated that heat treatment for homogenization did not substantially reduce crack sensitivity. Porosity closure was apparently responsible for the reduced weld cracking. Figure 13 illustrates the effect of temperature and pressure on Inconel 718 microstructure. The untreated, as-cast material is replete with voids and inhomogeneities. The 2190°F/4 hour treated material is homogeneous but still contains considerable porosity. Only the HIP densified Inconel 718 possesses both soundness and homogeneity. Initial manufacturing implementation of the process has fully realized the projected benefits.

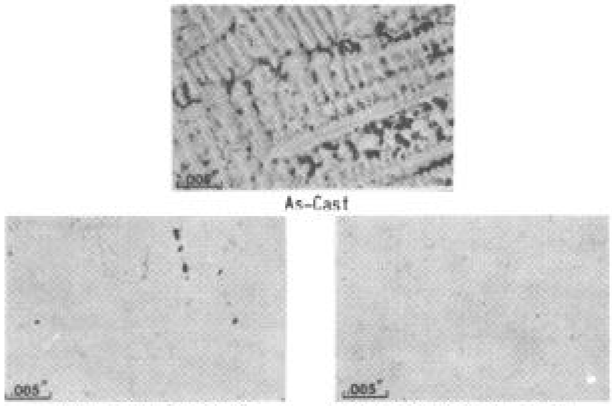
A compressor case cast flange, after electron beam welding to a forged casing, exhibited cracking in the cast material. It too was used as a study tool for weldability. Metallographic examination of the cast and solutioned structure showed poor homogeneity, resulting in cracks along brittle grain boundary phases. A similar flange casting was densified at 2175°F/15,000 psi/3 hours and then EB welded. Metallographic examination disclosed less grain boundary segregation and fewer cracks. Figure 14 illustrates the difference in the weldability of the non HIP'ed and densified material.

Improved Chemical Milling

Castings are not normally considered amenable to chemical milling because shrinkage porosity and inhomogeniety promote localized uneven metal removal and attack. HIP circumvents these faults and allows consistently good chemical milling results, as illustrated by the Figure 15 top view for Inconel 718.

Chemical milling studies on Ti 6Al-4V slab castings also showed that HIP processing promotes uniform removal rates and provides defect-free final surfaces. Figure 15 bottom view dramatizes the improved results for the HIP processed casting. Both samples had shrink determined by radiographic inspection. After HIP, that sample was radiographically sound. Shrinkage was manifested in the non HIP'ed chemically milled surface as deep pits. No pits appeared on the HIP processed slab.

The chemical milling experience with 17-4PH castings closely parallels the results on Ti 6Al-4V and Inconel 718. Chemical milling on non HIP'ed 17-4PH exposes numerous pits, whereas the final chemically milled surface on HIP'ed 17-4PH was free of defects as shown in the middle view of Figure 15.

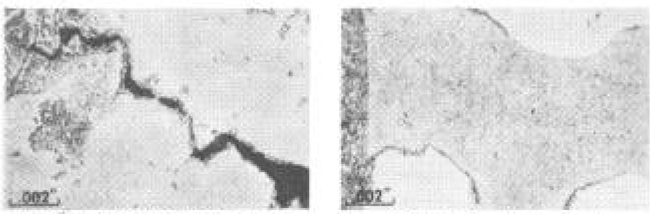


As-Cast

Vacuum Heat Treatment
2190F/4 Hours

HIP'ed 2190F/10,000 psi/4 Hours

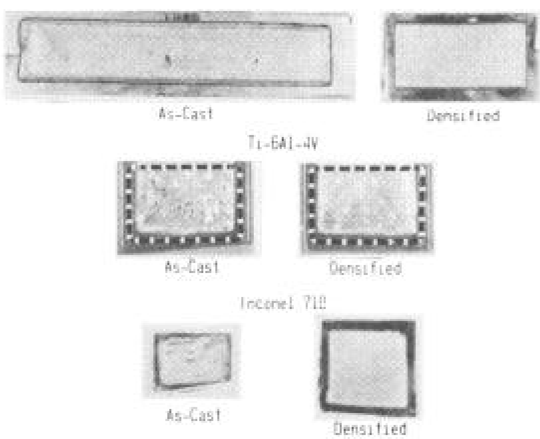
Figure 13. Microstructure of Inconel 718 Strut End Castings.



Non-HIP'ed Plus Heat Treat

HIP'ed Plus Heat Treat

Figure 14. EB Welds On Inconel 718.



As-Cast

Densified

Ti-6Al-4V

As-Cast

Densified

Inconel 718

As-Cast

Densified

17-4PH

Figure 15. Improved Chemical Milling On Various Alloys

Engine Component Manufacturing Considerations

Two basic measures of jet engine materials are performance and cost. Improved materials properties permit improvements in life, operating temperature capability, reduced weight, etc. The beneficial effects of HIP in improvement of mechanical properties (and hence performance improvements) have been discussed. Reduced costs by the use of HIP are equally attractive and include:

- Reduced NDI casting scrap.
- Reduced manufacturing scrap from undiscovered sub-surface defects uncovered in part machining and the avoidance of lost machining charges.
- Reduced welding costs.
- Reduced inspection costs.
- Improved properties allowing substitution of HIP castings for wrought parts.

Manufacturing Concerns

Successful introduction of HIP'ed parts to the component manufacturing process involves consideration of a number of factors which are listed in Table III in general terms for superalloy and titanium castings.

TABLE III

HIP Manufacturing Concerns

Alloy	HIP Factor	Manufacturing Concern
Superalloys	Oxidation	• Surface depletion
	Oxidation	• ID Cleaning (blades)
	Oxidation	• Coating (blades)
	Oxidation	• Brazing
	Cooling rate	• Properties (blades)
	Fixturing	• Dimensions
Titanium	Oxidation	• Alpha case
	Oxidation	• Weldability

It should be emphasized that the items listed are not expected to be barrier problems but must be considered in any rational application of the HIP process.

High-Integrity Premium Quality Castings

"High-Integrity Premium Quality" castings are conceived to be those castings which have been produced in such a manner that their physical integrity and mechanical properties have, with a high degree of statistical confidence, been upgraded to nearly the upper limit of what can be expected from material having a cast structure. The processing required for high-integrity castings will vary in detail with specific alloys and components, but basically comprises the integration and optimization of the following:

- Part design
- Alloy composition
- Casting practices
- HIP densification
- Heat treatment
- Quality Assurance

Attendant to the increased reliability and performance capability of high-integrity castings are the economic advantages of greatly decreased material losses from both machining and generation of unacceptable parts, significant reductions in nondestructive inspection requirements, and an expanding spectrum of applications for cast components.

Only the high-integrity aspect of the total concept has been utilized to date, although in a highly successful but incomplete manner. The applications have been "fix-it" type to solve specific part manufacturing problems such as high casting yield losses, expensive weld repairs, or high manufacturing yield losses. The premium quality part of the concept has not really been utilized yet, but substantial progress is being made.

Each alloy system will have its particular "premium quality" development needs. In nickel base blade alloys there are two major considerations. One is close coordination of HIP densification temperature parameters, cooling rates, and post HIP solution and age heat treatments. The second consideration is the minimization of atmospheric contamination in HIP which might aggravate cleaning and coating of intricate hollow blades. In superalloy frame and casing materials, such as Inconel 718, reducing the wide disparity between cast and forged properties requires the optimization and coordination of all applicable processes including:

- Composition optimization-especially the γ' formers
- Casting practices to achieve finer grain size
- HIP and heat treatment parameters to close porosity, eliminate brittle phase and optimize γ' morphology.

In titanium alloys, premium quality is expected to accrue to a large extent from void closure and homogenization of microstructures. Data from HIP'ed castings in Ti 6-4 and Ti 6-2-4-2 show that mechanical properties nearly equivalent to forgings are attainable.

In aluminum alloys, available evidence suggests that interstitial gas content can in some instances override simple HIP porosity closure and cause the recurrence of porosity in subsequent heat treatment.

In summary, each alloy has its own combination of premium quality process requisites beyond simple temperature, pressure, and time for porosity closure parameters. Proper selection and integration of the detailed processes are essential.