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Near-Net-Shape HIP Manufacturing for sCO2 Turbomachinery Cost Reduction

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Abstract. sCO2 turbomachinery that operates above 650°C requires the use of γ′ strengthened Ni-based superalloys, leading to high cost and barrier of market adoption. Near-net-shape (NNS) HIP manufacturing with 282® alloy powder is being developed for sCO2 turbine components, with a significant estimated cost reduction. Tensile, creep, low cycle fatigue properties of argon gas atomized and plasma atomized powders were evaluated and compared to sand cast HAYNES® 282®. While tensile strength and fatigue life outperformed sand cast material, a 10~25% debit in the creep stress capability was observed due to the fine grain size and presence of prior particle boundaries (PPBs). Finite element model calibrated by powder rheological properties accurately predicted the nonuniform shrinkage during HIP, providing HIP tooling design to achieve the target dimension. A 20 lbs. turbine nozzle ring was successfully demonstrated within 0.01 inch dimensional tolerance at the vanes. A 1700lbs. turbine casing with complex internal struts and manifolds was also demonstrated being close to the target dimension.

Introduction

Supercritical carbon dioxide (sCO2) turbomachinery that operates above 650°C requires the use of γ′ strengthened Ni-based superalloys, leading to high component cost and barrier of market adoption. Despite the 10X smaller size of a sCO2 power cycle than a steam power cycle, the LCOE of sCO2 power cycle in concentration solar-thermal power (CSP) remains to be a significant portion. HAYNES® 282® alloy with superior creep strength is a candidate for sCO2 turbine components. Supply chain is limited for large forging or casting in HAYNES® 282®. Initial attempt to sand cast a multi-piece turbine casing was not successful because of casting defects that required extensive weld repair, while extensive machining associated with massive material waste and high cost would be required if starting with a large forging. Therefore, alternative manufacturing route of powder metallurgy (PM) NNS HIP is being explored to reduce the cost of static turbomachinery components. In the present work, mechanical properties of PM HIP 282® alloy, NNS HIP feasibility of turbine nozzle ring and casing, technoeconomic impacts were evaluated.

Mechanical Properties of PM HIP 282® alloy

Argon gas atomized (GA) and plasma atomized (PA) 282® alloy powder were acquired for evaluating tensile, creep, and low cycle fatigue (LCF) properties of PM HIP 282® alloy. Despite the higher cost than GA powder, PA powder has the advantages of improved cleanliness, highly spherical morphology, low trapped gas/porosity, high yield in the powder size range appropriate for PM HIP. GA powder used was 53~150um in size with 62% relative tap density. PA powder used was 20~180um in size with 67% relative tap density. PA powder contains lower oxygen than

GA powder (compositions shown in Table 1). HIP condition of 1204°C/15ksi/4hr was performed on lab-scale HIP cans. The resulting average grain size measured by EBSD was 17um and 22.6um for GA and PA powder, respectively. A representative PA powder HIP microstructure is displayed in Figure 1d. Titanium rich MC carbonitrides and aluminum rich oxides were observed to decorate the PPBs and effectively pin grain boundary motion. The lower oxygen in PA powder is believed to introduce lower amount of PPB particles and thus leading to a slightly larger grain size. Solution treatment (1149°C/1hr/WQ) followed by two-step aging treatments (1010°C/2hr/WQ + 788°C/8hr) was applied after HIPing.

Mechanical properties of PM HIP 282® alloy were tested at relevant operating conditions and compared to wrought, sand-cast, and forged materials in literature [1-2]. As plotted in Fig. 1, PM HIP reveals significantly higher yield strength and ultimate tensile strength (UTS) than sand-cast and even higher than wrought, possibly owing to its fine grain size. PM HIP shows similar magnitude of tensile elongation with sand-cast, but 10~15% lower than wrought. Each data point represents an individual test. A smaller sample-to-sample variation in PM HIP than sand-cast material is noticed. PA powder slightly outperforms GA powder in tensile strength and ductility at elevated temperatures. Creep rupture tests were conducted at 1400°F to generate the Larson-Miller plot in Fig. 2a. A 10~15% debit in the creep stress capability is observed in PA powder HIP vs. wrought or sand-cast materials. The limited data of GA powder HIP at high creep stress indicate its inferior creep resistance than PA powder. The PPB network and finer grain size are likely to contribute to the lower creep ductility and faster creep rates in PM HIP materials. Both GA and PA powder HIP exhibits fatigue property superior to sand-cast and wrought materials (Fig. 2b). GA powder HIP shows slightly longer LCF life than PA powder at 0.7% and 0.6% strain ranges, while similar life is observed at higher strain range of 0.9%. PA powder was selected for NNS HIP part demonstration given the better creep resistance than GA powder.

Table 1. PA and GA 282® alloy powder compositions vs. nominal composition

(weight percent, wt.%)

Alloy	Ni	Cr	Co	Mo	Al	Ti	C	B	N	O
Nominal	Bal.	20	10	8.5	1.5	2.1	0.06	--	--	--
PA powder	Bal.	19.4	10.4	8.4	1.6	2.1	0.06	0.003	0.006	0.007
GA powder	Bal.	19.3	10.2	8.3	1.6	2.1	0.05	0.004	0.006	0.013

Turbine Nozzle Ring Demonstration

A 20 lbs. turbine nozzle ring was first selected to demonstrate the feasibility of NNS HIP with 282® alloy. Powder rheological properties were measured to calibrate the finite element HIP model, including specific heat, density, coefficient of thermal expansion, thermal conductivity in fully densified material up to the HIP temperature, yield stress as a function of density in fully and partially densified material. The HIP tooling design (Fig. 3a) was guided by the HIP simulation to achieve net shape at the vanes. The manufactured HIP tooling with carbon steel (Fig. 3b) had an insert (Fig. 3c) placed into the canister with features to position the nozzle ring correctly. The insert being a separate piece allowed more conventional machining operations to be used. After the tooling was assembled and welded, PA powder was filled through the stems, outgassed (Fig. 3d), and helium leak checked. The part went through HIP cycle, pre-machining to produce a sonic shape for immersion ultrasound inspection (Fig. 3e), and acid leaching in a HCl based solution to remove the carbon steel tooling and reveal the nozzle ring (Fig. 3f). After a first nozzle ring was fabricated, trailing edge defects (traces of machining tool, incomplete profile of trailing edge) were observed, which originated from vibration/bending/deflection of the needle tool during the insert slot machining. HIP model of nonuniform shrinkage and HIP tooling design were validated by the resulting dimensional tolerance of the first nozzle ring (vane within ±5mil, hub and shroud within ±10mil). Improvements were made in a second nozzle ring by enlarging the trailing edge to allow the use of a larger deflection-free tool in 5 axis milling. Chemical milling was added after acid leaching to meet the target dimension as well as removing the interdiffusion layer at the can and powder interface. The second nozzle ring successfully eliminated the trailing edge defects and tool marks (Fig. 3g, 3h). All vanes were of exceptional uniformity and repeatability. Dimensional inspection (Fig. 3i) shows a vane contour close to the target dimension with all the surfaces 15~20mil undersized except trailing edge. The problem was identified as faster chemical milling rate on the vanes than the pre-machined shroud surface. It was speculated that the powder profile and the interdiffusion layer of the vane surface could be more susceptible to chemical milling. Average surface roughness was Ra 6.2µm on pressure side and Ra 3.7µm on suction side of the vanes, suggesting that superfinish (a well-established process) would be required to achieve the target roughness of Ra 3.175µm. These encouraging results and learnings were then applied to the turbine casing NNS HIP demonstration.

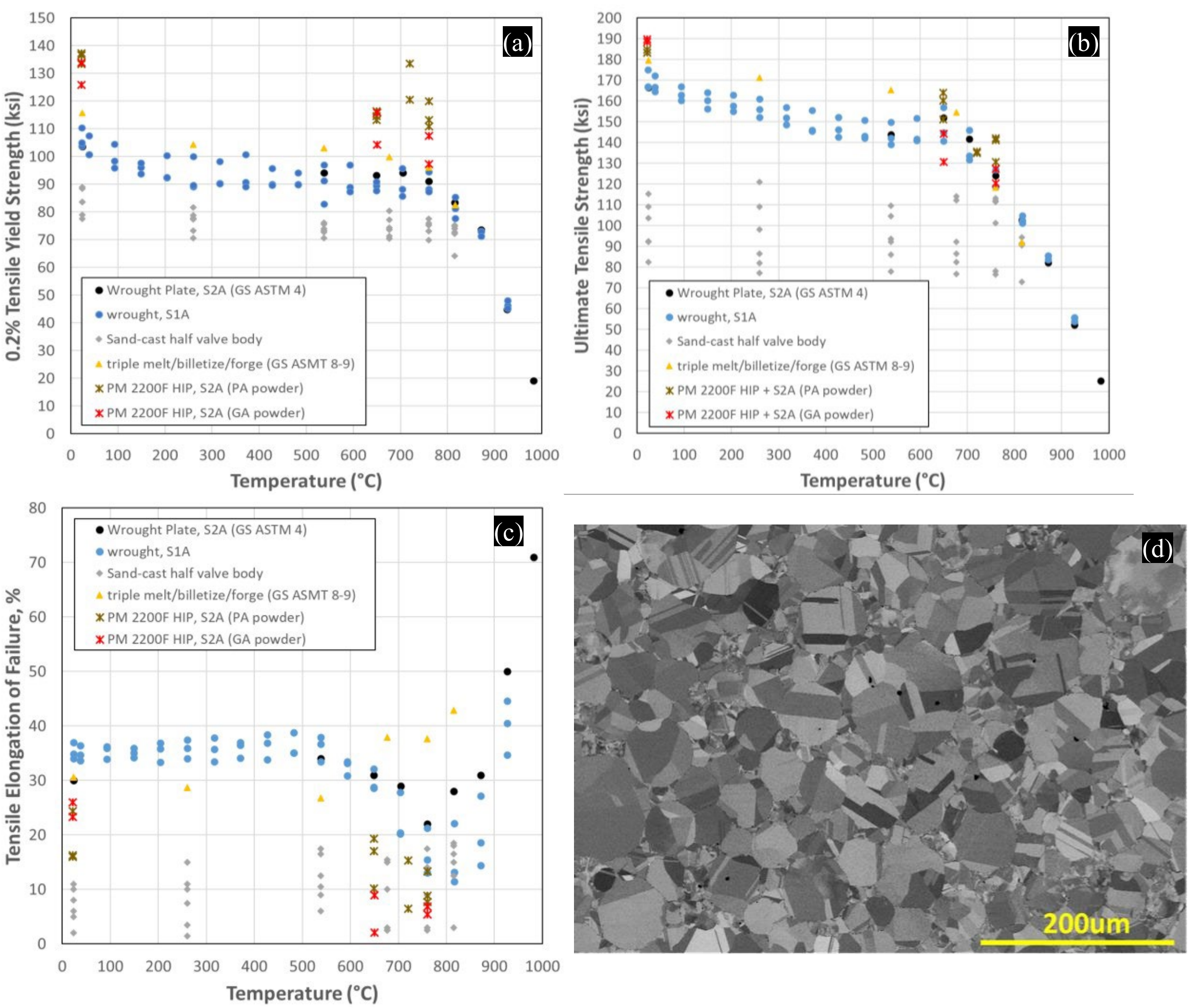

Figure 1: (a) 0.2% yield strength, (b) UTS, and (c) tensile elongation of PM HIP 282® alloys in comparison with wrought, sand-cast, and forged HAYNES® 282®. (d) Typical HIP microstructure of PA powder in a backscattered electron image.

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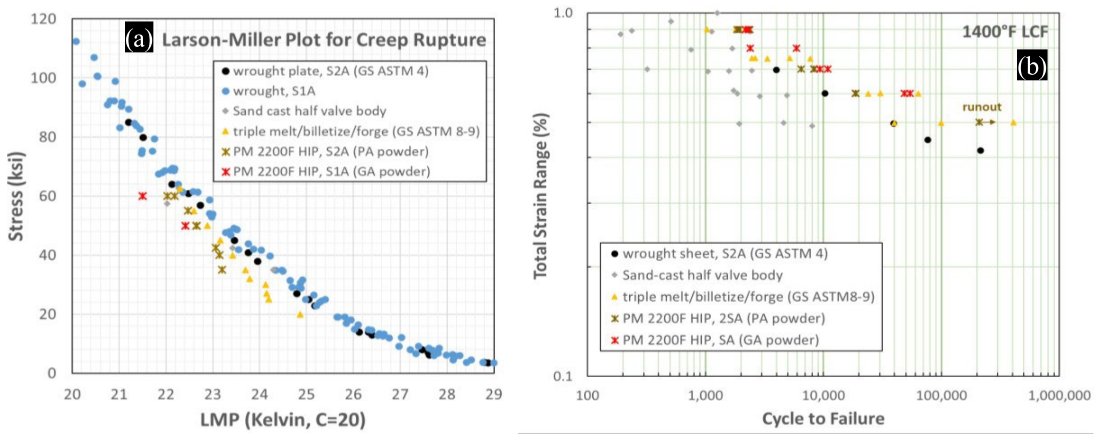

Figure 2: (a) Larson-Miller plot for creep rupture and (b) 1400°F LCF properties of PM HIP 282® alloys in comparison with wrought, sand-cast, and forged HAYNES® 282®.

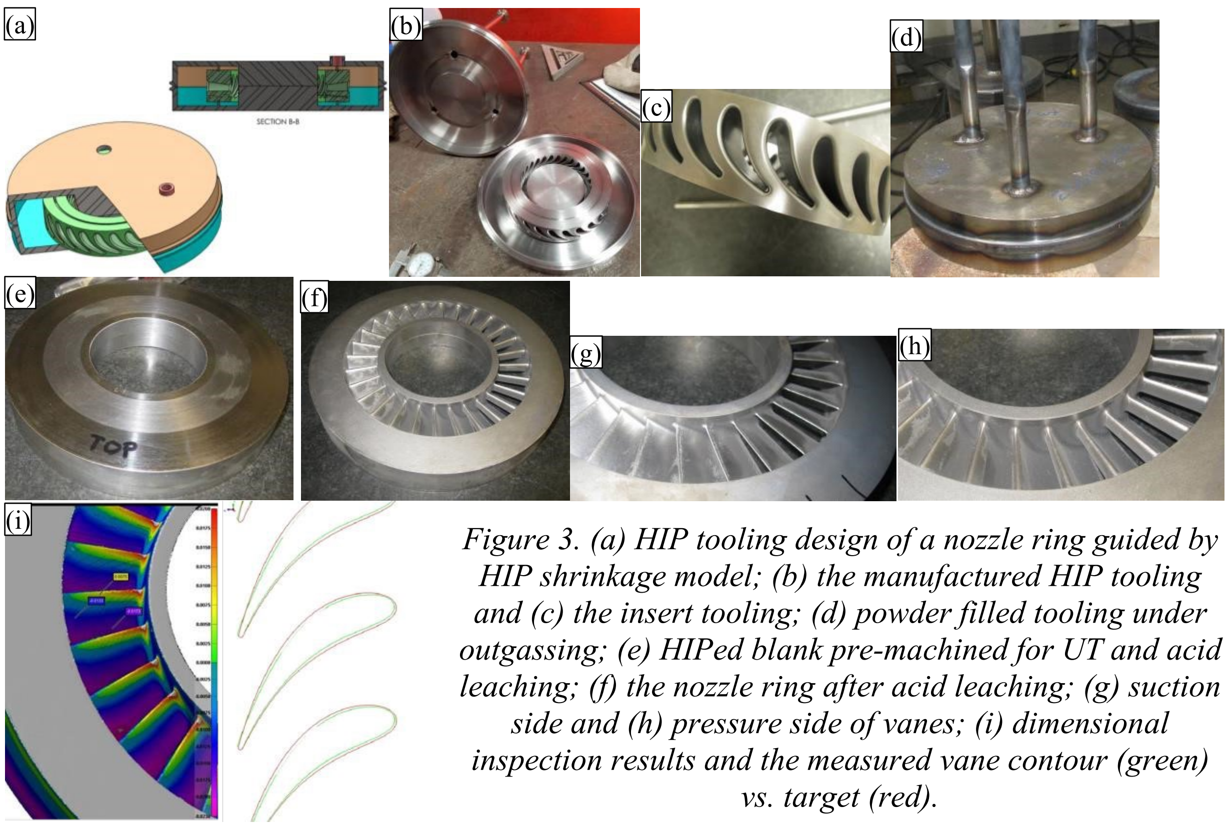

Figure 3. (a) HIP tooling design of a nozzle ring guided by HIP shrinkage model; (b) the manufactured HIP tooling and (c) the insert tooling; (d) powder filled tooling under outgassing; (e) HIPed blank pre-machined for UT and acid leaching; (f) the nozzle ring after acid leaching; (g) suction side and (h) pressure side of vanes; (i) dimensional inspection results and the measured vane contour (green) vs. target (red).

Development of the 282® alloy turbine casing via PM NNS HIP had to address several technical challenges caused by the new material, size, shape and internal geometry, including HIP tooling design and fabrication (Fig.4a-c), powder filling/outgassing, HIP (Fig. 4d), dimensional control, NDT inspection, de-canning (Fig.4f). With the powder weight in the HIP can exceeding 1700 lbs., a massive non-uniform shrinkage (exceeding 10% linear, or several inches per main dimensions) had to be predictable and considered in the HIP tooling design. The non-uniform shrinkage was influenced by the powder rheology properties, plastic stiffness of the HIP can during HIP, the 3D effects caused by the external ports, and most important, internal tooling elements (inserts) forming the manifolds and the struts. The HIP tooling manufacturing involved several techniques of sheet material fabrication and very precise 3D CNC machining that had to be matched in assembling and welding to provide a perfect fit, avoid distortions, ensure a vacuum tight assembly that will survive the 2200°F HIP with severe deformation of the welds. Despite a good flowability of the

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282® PA powder, filling a volume with numerous inter-connected cavities required an intricate filling system to ensure uniform filling. Most of the filling ports also served as multiple outgassing exit channels, but still due to the molecular flow of gases inside the powder bulk, high vacuum combined with elevated temperature and time was mandatory to remove the physically adsorbed air and moisture from the surface of the powder particles to ensure full consolidation and further re-crystallization. HIP is a well-established process but has its own "under-water stones" when large PM parts, taking most of the furnace volume are processed. With the excellent uniformity of temperature at the hold stage due to high density of argon, the ramp stage of the HIP trajectory has usually high temperature gradients along the height causing earlier deformation of HIP capsules in their upper part. This was also accounted in the HIP tooling design to minimize distortions. As a result, in addition to reaching the 100% density (confirmed by the TIP tests and microstructure), the turbine casing adequately reproduced the shape from the FEM simulation (Fig. 4g) with small distortions and deviations found after scanning and dimensional analysis can be amended within the 2nd iteration of the tooling. During HIP the capsule perfectly bonds to the Ni base powder "substrate", this has allowed to produce ultrasound inspection with the HIP tooling on, when the internal volumes are still "solid", and to inspect then "through the steel" the intricate internal features of the manifolds with the two arrays of vanes/struts. The HIP tooling removal was done by acid leaching and presented several challenges, mainly due to the weight and size of the parts and the amount of the steel to be removed. Due to the HIP tooling design leaving the main inserts hollow and vented during HIP, it was possible to provide an efficient tooling removal from the vanes and manifolds without "dead" zones inside that could cause gaseous products and chemical attack of the alloy. While the outside geometry of the turbine casing was accessible for the final machining, the internal geometry was not and the goal was to provide the "net shape" of the 3D structs and manifolds. The dimensional analysis done after sectioning revealed a good correspondence and the possibility to reach 20~40mil tolerances for the 2nd iteration.

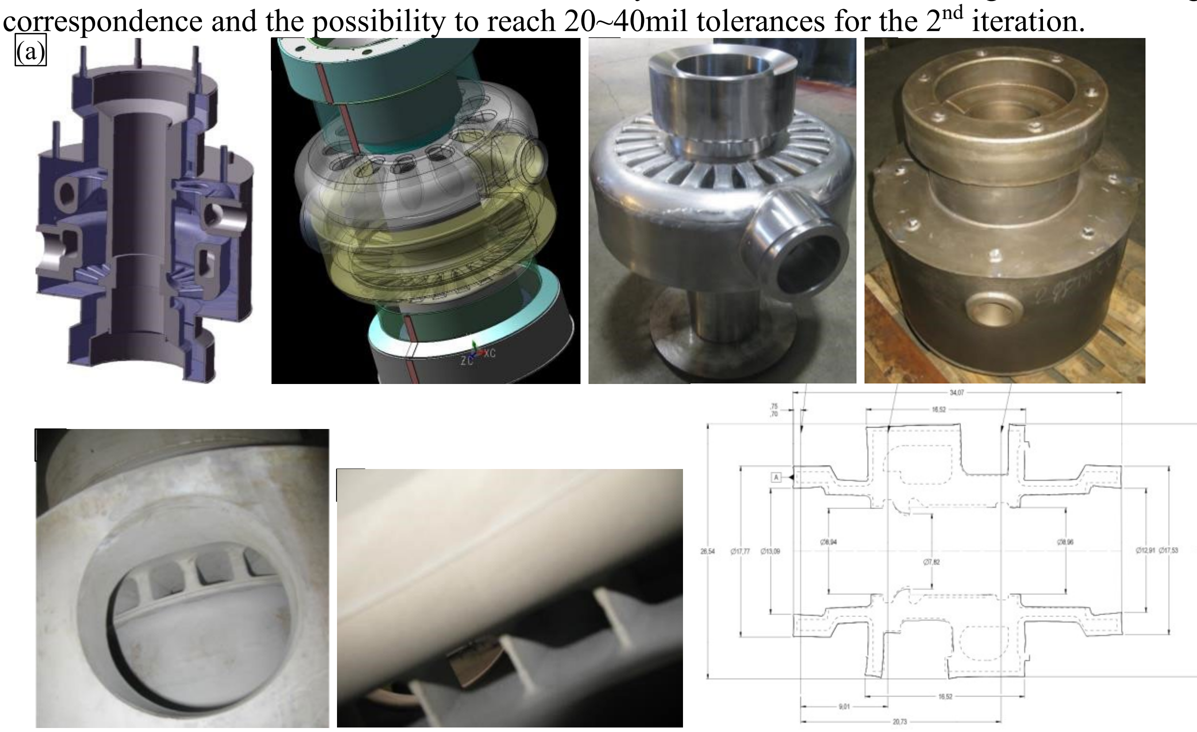

Figure 4: (a) CAD model of turbine casing HIP tooling; (b) CAD model of two internal inserts assembled with ID steel tooling; (c) assembly of internal vented tooling to form manifolds and struts; (d) HIPed part; (e) and (f) internal struts free of carbon steel tooling after acid leaching; (g) the HIP deformation map of the turbine casing.

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Technoeconomic Analysis

A detailed cost model of NNS HIP based on US manufacturing was performed for the nozzle ring and compared to current manufacturing processes and the actual hardware costs for the 3 stages of nozzle rings that make up the turbine under the STEP program (DE-FE0028979). Those nozzle rings were created from forgings, with initial rough machining using conventional multiaxis mills followed by multi-axis plunge EDM operations to create the vanes. As the STEP nozzle rings were not produced from HAYNES® 282® alloy, material cost adjustment was made. The estimated cost for forged and machined complete set of 3 nozzle rings is $408,124 ($33,124 in material, $375,000 in machining). For the NNS HIP process, the costs of manufacturing 3 nozzle rings are broken into powder cost of plasma atomized powder in small lot ($3,933), Non-Recurring Engineering (NRE) ($30,000), NNS HIP process including HIP tooling, powder filling/outgassing, HIP cycle, acid leaching ($83,500), post-processing including heat treatments and final machining ($22,500). The total cost estimate for NNS HIP ($139,933) is only 34% of the conventional. 20 STEP turbines were considered to show the volume cost reductions. Costs reduce slightly as the NRE costs are amortized over a larger volume as well as a small reduction in NNS HIP costs. The NNS HIP costs are not reduced significantly due to the current HIP conditions that require a HIP unit which has a limited volume capacity and therefore can only hold 2 turbines worth of stages in a single HIP operation. The cost estimate becomes $110,183 per turbine, suggesting a 21% cost reduction on volume basis compared to a single unit. The NNS HIP process cost is dominant, well over 3x the post processing costs, the 2nd highest. NNS HIP manufacturing provides a significant LCOE reduction (> 75% $/kW reduction) over the conventional manufacturing for sCO_2 turbine.

The impact of creep debit in PM HIP 282® alloy can be offset by increasing the wall thickness of the turbine casing only at the creep limiting locations, per ASME BPVC code Part III Section D. A 13% wall thickness increase is required to match the creep capability of sand-cast material, resulting in 35lbs additional powder and a marginal effect on the cost. On the other hand, pipe components made by NNS HIP are projected to have a larger cost penalty due to creep property, given the uniform wall thickness. Comparing PA and GA powder for a pipe fitting component, GA powder would need 12% wall thickness increase (30% more powder mass) than PA powder due to its creep deficiency.

Summary

NNS HIP fabrication with 282® alloy powder was demonstrated to be technically feasible and economically viable for sCO_2 turbine components (nozzle ring and turbine casing). Dimensional tolerance was met for the vanes and complex internal struts and manifolds. Despite the superior tensile and fatigue properties, the creep debit in PM HIP material is intrinsic to its PPB network and fine grain structure. A cost-performance tradeoff by increasing wall thickness to compensate creep is highly dependent on the design requirements of the components.

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