Technical paper: Powder metallurgy methods for producing large components

The manufacture of large, complex components will be extremely costly for the power industry over the next few decades as many of these will be produced from expensive, high strength alloy castings and forgings. EPRI is investigating the use of an alternative manufacturing method, powder metallurgy and hot isostatic processing to produce high quality and potentially less expensive components for power generation applications. Benefits of the process include manufacture of components to near-net shapes, precise chemistry control, a homogeneous microstructure, increased material utilization, good weldability, and improved inspectability.

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Powder metallurgy (PM) technology integrated with advanced modeling/design capabilities and state-of-the-art hot isostatic processing (HIP) technology, can support the energy industry's efforts to increase efficiency, reduce emissions and lower installation and operating costs. The manufacture of large and complex components with PM/HIP technology can provide an alternative method to current processes such as forging and casting. Benefits of making near net shapes (NNS) via PM/HIP includes precise chemistry control on any stainless steel or nickel/cobalt alloy, increased material utilization, elimination of welding, and improvement in inspectability.

EPRI has evaluated the processing and manufacturing of a radically different method for manufacturing very large complex near-net shapes for use in electrical power generation equipment. This technology has the potential to increase plant reliability and safety, reduce manufacturing energy use and processing waste, and diversify the domestic supply base for the electrical generation industry. The process proposed will demonstrate significant advancement in manufacturing methodology for the large components required predominately for advanced fossil and nuclear power plants. The technology is transformational and would shift the current technology base for manufacturing these components from forging and/or casting to a more cost effective powder metallurgy (PM) processing technology.

It is anticipated that large, complex components could be produced for nuclear, ultra-supercritical, and oxy-combustion plant applications including pump housings, valves, sweepolets, tees, flanges, steam chests, nozzles, elbows, turbine casings, canister plugs, and other components which are currently cast for power plant use. PM technology would minimize or eliminate current issues associated with microstructural and mechanical property uniformity, welding difficulties, heat treatment problems, and inspectability in large components. It would also provide an ideal path for manufacturing, addressing a short-term need for fabrication of complex components. In addition, the PM technology would increase material utilization (hence reducing energy utilization on a per component basis), reduce machining operations, and significantly reduce manufacturing and delivery times. PM technology could allow the use of new alloy systems with high temperature strength, creep resistance, and corrosion/erosion resistance that will enable power generation systems to operate at higher temperatures and pressures and for longer periods of time, which will measurably increase plant efficiency and availability. Once accepted, PM technology would provide additional longer-term transformation opportunities by custom tailoring alloy compositions or manufacturing bi-metallic components for specific applications.

Researched for nuclear power

Considerable research has been completed over the last decade to characterize PM/HIP for potential use in nuclear applications. Specifically, Rolls Royce has produced a number of research papers surrounding the development of data for 316L stainless steel to be used in nuclear components. Their research has shown that high quality 316L SS components (thick section tees, large valves, valve seat inserts, and thin-walled toroids, etc.) can be produced with superior mechanical and microstructural

Figure 1. A 780kg (1716 lbs), 316L prototype stainless steel valve body produced during the feasibility assessment. The valve body was sectioned along its center line to reveal its ability to produce a sound, dimensionally stable, component configuration.

properties. Rolls Royce has also explored the use of Inconel 600 and 690 powders for component manufacture.

Carpenter Technology, in addition to supplying gas atomized powder for many PM/HIP applications, has investigated PM components to demonstrate properties, corrosion resistance, etc. manufactured from stainless steels, borated stainless steels, duplex stainless steels and various high temperature alloys. In all cases the PM materials met or exceeded the capabilities of cast or cast and wrought materials.

Research has also been undertaken by the VTT Technical Research Centre of Finland and Helsinki University. Their research includes manufacture and assessment of duplex stainless steels for paper machine roll applications, nitrogen containing austenitic stainless steels for wear applications, 316LN austenitic stainless steels for light water reactor applications, and investigation of oxide dispersion strengthened (ODS) alloys. ASTM currently recognizes two standards, one for producing HIP alloy (ASTM A989) and stainless steel flanges, fittings, valves, and parts (ASTM A988).

What is powder metallurgy?

Powder metallurgy is a forming and fabrication technique that consists of: 1) component design, 2) manufacturing of a metallic powder normally by gas atomization, 3) loading of the powder into a mold or die with a packing density of 60-70%, 4) degassing and sealing the mold with the contained powder, and 5) consolidation (HIP) by applying high temperature and pressure. HIP is a solid state diffusion process that produces fully dense microstructures with no porosity.

Component Design. Component design includes creation of a 3-D model for the component. With this model, a mold or container that replicates the final component can be produced to contain the powder (more on this subject below). It is also important to point out that component design includes alloy design. With the PM/HIP process, the manufacturer can tailor a specific composition to control specific elements such as boron, carbon, or various tramp elements.

Powder Atomization. Powders are routinely manufactured today through a process known as gas atomization. In this process, a material is induction melted at a high temperature and forced through an orifice (nozzle) at moderately high pressures. A gas is introduced into the molten metal stream just as it leaves the nozzle, creating significant turbulence as the entrained gas expands (from heating). At this point the gas exits into a large collection volume outside of the orifice. The collection volume is filled with gas to promote further turbulence of the molten metal. Gravity or cyclonic separation is used to separate the resulting spherical powder particles of varying sizes and air or gas. The resulting powders are then screened to remove oversized particles and blended to produce a uniform powder size distribution for the intended use. It is important to point out that powder atomization produces considerably higher quality powders than those produced through powder milling operations. As such, oxidation issues associated with earlier PM/HIP processes are significantly reduced and in many cased eliminated entirely.

Molding (or Container). The third step in the PM/HIP process is the manufacture of a mold or container to contain the atomized powder during processing. The mold (container) is manufactured to a size slightly greater than the component using the component design drawings established at the beginning of the process. Metallic containers are most often used for the production of large components.

Powder Consolidation, Vacuum Processing, and Hot Isostatic Processing. After the mold or container is completed, the powder is packed into the mold/container and brought to temperature under a high vacuum to consolidate and densify the powder. This process involves simultaneous application of high isostatic pressure and heat ranging from 500 to 1200°C (900 to 2200°F) to compress and consolidate the powder within the mold. The process is normally conducted under an inert gas (argon) atmosphere and pressures can range from 7,000 psi to 45,000 psi, with 15,000 psi being the most common.

Why Consider PM/HIP for large components?

Large power generation components are commonly fabricated by conventional "tried-and- true" metallurgical processing methods

Figure 2. Photographs showing manual and automated inspection of the valve body in process.

including: casting, rolling, drawing, forging, extrusion, welding, and heat treatment. These processes have been used to fabricate components all the way back until the early part of the 20th century. As materials processing practices have improved over the years, higher quality components have resulted, including super-clean forged rotor and disc steels, directionally solidified and single crystal blade alloys, controlled residual element alloys, creep-strength enhanced ferritic piping/headers, and improved component surfacing techniques. One area that has seen remarkable improvements in processing technology is powder metallurgy, where component quality, availability, and size have increased dramatically within the past 25 years.

Powder production facilities currently exist to manufacture large quantities of powder for high quality alloy steels, stainless steels and nickel base alloy parts. Hot isostatic processing (HIP) facilities are also available to manufacture large shapes, and such facilities have been demonstrated to a limited extent for specialized aerospace, oil exploration, tools, and other niche applications. High quality components showing good structural uniformity, no segregation, superior mechanical properties, and ease of inspectability have been produced from a number of stainless steels and nickel base alloys. Large PM produced components have not been utilized in the power generation industry to date primarily due to three technical barriers:

- The sizes and shapes for near-net shaped PM-produced components have only recently reached a point for consideration and have not been tailored for the compositions/alloys that are of most interest to the industry.
- Materials and processes utilized to manufacture pressure retention or high temperature power plant components are generally subject to, in the U.S., the ASME Boiler and Pressure Vessel Code which currently does not allow the use of PM produced components for the desired applications.
- For iron-based steels alloy systems, the PM/HIP production route is generally more expensive than traditional forging and casting routes. However, for stainless steels and nickel-based alloys, where raw material costs are much higher, PM/HIP appears to be a cost effective solution.

These barriers can be overcome with focused research. EPRI, (in conjunction with Carpenter Technology Corporation), has set out to explore how and where PM technologies might be brought to the power industry. PM technologies exhibit several attributes that make it attractive to the power industry:

- Eliminates inspectability issues and concerns
- Enables manufacture of large, complex components using near-net shape technologies
- Enables new alloy systems & targeted chemistries
- Enhances weldability
- Provides an alternate supply route for long-lead time components
- Eliminate re-work or repair of large cast components.

Inspectability. Inspection of large cast components including pump housings, valve bodies, elbows, flanges, sweepolets, steam chests, turbine casing shells, nozzles and canister plugs is challenging due to the non-homogenous microstructure within castings. Castings can contain voids, pockets, segregation of tramp elements, inclusions, hot tears, secondary phases and non-metallic particles that make inspection of cast components difficult. The use of PM to produce alloys and components results in a very uniform, homogenous microstructure that is inspectable in terms of both detection and sizing.

Near-Net Shaped (NSS) Components. One of the highly desirable attributes of producing components via PM/HIP processing methods is the ability to produce components in a near-net shaped condition which requires only minimal machining and clean-up. Cast components are commonly fabricated in an "over-sized" condition to allow for irregularities that may occur along the length of the component. Components produced with PM/HIP can be produced very near final shape, resulting in reduced component weight, reduced machining, and ultimately saving dollars in the overall production of the component. Production by NNS technologies also reduces energy and processing waste during the fabrication process.

New Alloy Systems and Chemistries. Another attribute of PM/HIP processing methods is the ability to alter (or design) the chemistry of a specific component on a component-by-component

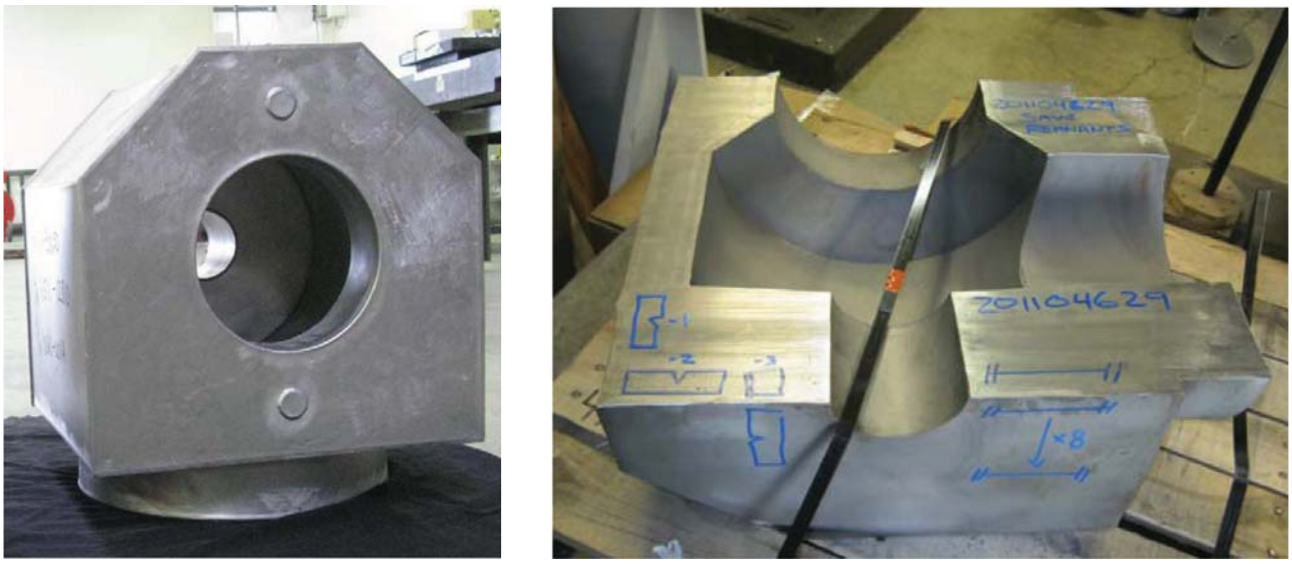

Figure 3. Three 316L stainless steel valves were manufactured by Carpenter Technology to drawing/specifications provided by Tyco Crosby. The valve body shown on the left is the finished valve body. The photograph on the right shows the valve body after it has been sectioned into halves.

basis. No longer will a melter/fabricator have to produce a large (several ton) heat of material to fabricate an individual component. Fabricators will now be able to produce individual components (or heats of material) using a specified chemistry. Furthermore, PM/HIP technologies now enable the production of new alloy systems. For example, if one wants to control a particular element such as boron or carbon or a residual element such as sulfur or phosphorous, PM/HIP allows for specific control of one or more of these elements.

Enhanced Weldability. Cast components are often difficult to weld due to the irregularities in microstructure of the component. Even within one specific alloy system (or materials specification), the weldability of a cast component can vary greatly. The homogeneity of PM/HIP produced alloys eliminates the weldability concerns almost entirely. Once a particular chemistry has been selected, it can readily be reproduced over and over with minimal differences in weldability.

Alternate Supply Route for Long-Lead Time Components. When constructing advanced nuclear and fossil generation plants long lead-times are commonly encountered since only a limited number of manufacturers are available to produce components for the power industry. Introduction of PM/HIP technologies within the ASME Boiler Pressure Vessel Code will provide utilities with an alternate supply route for components. Manufacturing times will be significantly decreased and overall costs will be reduced.

Elimination of Rework or Repair of Large Cast Components. One additional attribute of PM/HIP technology that cannot be overlooked is its ability to produce homogeneous microstructures which substantially reduces the number of repairs required in castings. In discussions with various valve manufacturers, it is not uncommon for large cast components to require 10-50% repairs to eliminate casting defects depending on the casting house used. This represents considerable rework and overall lifecycle cost to the manufacturer, which is often not taken account of in the purchase of the casting. Such findings also bring into question the integrity of cast components, which leads to overdesign in many cases. PM/HIP can eliminate the need for this rework.

Part I – Initial feasibility assessment

The initial feasibility assessment involved the production of a 316L stainless steel valve body. A general valve body design of a 12-inch diameter valve was provided to Carpenter Technology Corp. for the production of the demonstration valve. Upon completion of the container, the powder was introduced into the container and the component was HIPed. The resulting component is shown in Figure 1. The valve body was provided in the annealed condition and weighed 780kg (1716 lbs). Upon receipt of the valve body from Carpenter Technology Corp., EPRI provided the component to its inspection team for characterization.

Inspection: The valve body was highly inspectable and presented no inspection challenges to the ultrasonic inspection process (Figure 2). Similar studies using standard non-destructive evaluation techniques on cast 316 stainless steel have shown the material to be not inspectable with ultrasonic inspection techniques.

Weldability: Several test coupons were produced using PM/HIP to the 316L stainless steel specification. The PM/HIP plates provided welding characteristics comparable to those of a typical forged stainless steel component.

Valve body assessment: The sectioned valve body provides some perspective on the ability of the process to produce intricate shapes and configurations. No finish machining was performed on the part.

Metallographic characterization: The microstructure was predominately austenitic with some isolated carbides observed throughout the matrix. An ASTM grain size of 6-7 was measured which is consistent with that of a solution heat treated stainless steel alloy.

Chemical composition: Widely available atomized powders produced by Carpenter Technologies were utilized to produce the valve body.

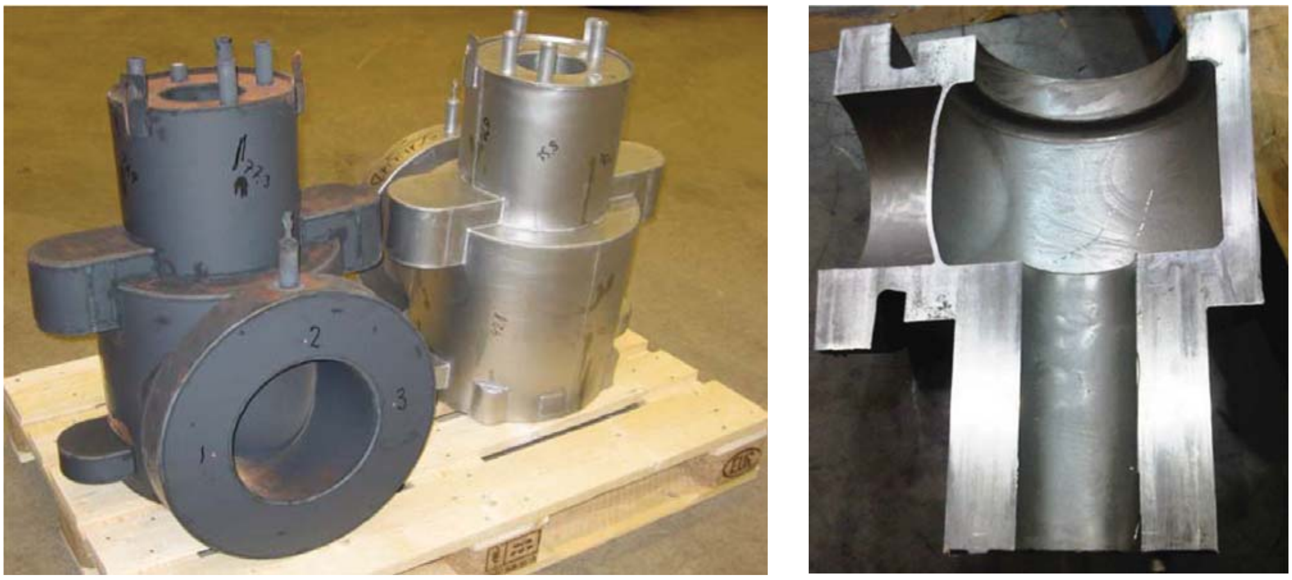

Figure 4. Three Grade 91 alloy steel valves (such as the one on the left) were manufactured by Carpenter Technology to drawing/specifications provided by Dresser. The valve body shown on the right of the first photograph is manufactured from IN625. The figure on the right shows a Grade 91 valve body that is sectioned into two halves.

Mechanical testing: The initial test results determined the toughness to exceed 195 ft-lbs or the capacity of the machine.

Part II – Manufacture of valve bodies

During the latter half of 2010 EPRI initiated a more targeted research program to focus on the development of several additional valve bodies of varying materials to support ASME Boiler Pressure Vessel Code Cases. A variety of valve body configurations were manufactured from three different alloys: 316L stainless steel (for nuclear applications), Grade 91 (fossil applications), and IN625 (ultra-supercritical applications).

EPRI and Carpenter elected to team with Tyco Valves to manufacture and test three 316L SS valve bodies. The three valve bodies were manufactured to Tyco's drawings/specifications, which allowed them to put the valve bodies through their rigorous testing criteria and production machining process. A photograph of one of the valve bodies is provided in Figure 3. Mechanical tests and metallographic characterization were completed for each valve body and are to be used in the assembly of a Code data package. Charpy impact toughness data exceeded 195 ft-lbs along three orientations for this alloy.

In parallel, EPRI and Carpenter also initiated production of three Grade 91 valve bodies in conjunction with another major valve manufacturer, Dresser. Teaming with Dresser allowed for component testing and production machining characterization in a similar manner that would be employed for actual valve production. A photograph of one of the valve bodies is shown in Figure 4. Initial mechanical tests and metallographic characterization are underway for each valve body and will be used in the assembly of a Code data package. A rigorous test matrix has been developed for creep and stress-rupture testing to support a potential 2012 Code package for this alloy.

Ultra-supercritical applications will require the use of solid-solution strengthened and precipitation hardened nickel-based alloys to meet the demanding temperatures and pressures required for such applications. As a feasibility assessment, one IN625 valve body was manufactured to assess component manufacturing potential. A photograph of the component is shown in Figure 4 (right side of first photograph).

Conclusions

This study determined that PM/HIP can indeed produce NNS components which exhibit metallurgical and mechanical properties meeting or exceeding those of conventionally cast or forged components. Mechanical properties produced in testing under this evaluation showed a 15% improvement over cast components of the same alloy (in terms of tensile properties), as well as exceptional toughness properties exceeding those of a 195 ft-lb test machine. Furthermore, it was demonstrated that significantly enhanced inspectability was achieved for the 316L stainless steel valve body produced in this effort over conventional casting components. Lastly, no weldability issues were encountered.

The second half of the study demonstrated that large components (valve bodies) can be manufactured using the PM/HIP process with 316L stainless steel, Grade 91 steel, and IN625 nickel-based alloys. In all cases, the tensile properties easily met or exceeded the Code requirements, as well as provided excellent toughness values. Homogeneous microstructures were observed for each component.

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