ELECTRIC POWER RESEARCH INSTITUTE

Quick Insight Brief: Manufacture of Nuclear Components Using Powder Metallurgy and Hot Isostatic Pressing

RESEARCH QUESTION

What impact can powder metallurgy-hot isostatic pressing (PM-HIP) have in the production of small modular reactor (SMR) and advanced reactor (AR) structural and pressure-retaining components over the next few decades?

KEY TAKEAWAY

The manufacture of large, structural and pressure-retaining components produced with PM-HIP technology can provide a cost-effective alternative to current processes such as casting, forging, drawing, and extrusion that results in highly inspectable parts that can be produced in the near-net-shaped condition minimizing the overall machining requirements.

KEY POINTS

- PM-HIP technologies are recognized by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) via Code Cases (CCs) and directly within ASME standards. ASME Code Cases include the following:
    - 316L stainless steel (CC N-834)
    - Grade 91 (9Cr-1Mo) steel (CC-2770)
    - Duplex stainless steel (CC-2840)
- BPVC-II: Materials – Mandatory Appendix 5: "Guidelines on the Approval of New Materials Under the ASME Boiler and Pressure Vessel Code" recognizes PM-HIP products in a similar manner to other product forms (forging, casting, and so forth).
- Medium/large, complex austenitic stainless steels components produced by PM-HIP are similar in cost with forged product forms. Because these components can be produced as near-net-shaped products, machining costs can be reduced, and delivery times can be lowered to four to six months versus two to five years for large components produced by forging processes.
- The homogeneous nature of PM-HIP material makes such products readily inspectable along all three primary directions, making them ideal for nuclear applications.

TODAY'S METHODS USED FOR MANUFACTURE OF NUCLEAR COMPONENTS

Large components used in today's nuclear applications are commonly produced using casting, forging, drawing, or extrusion technologies. Components produced by these technologies include reactor vessels, steam generators, pressurizers, valves, pump housings, piping, tubing, flanges, and fittings.

Various characteristics of each of these manufacturing technologies can present difficulties either during manufacturing or after the component has been placed into service, as follows:

- Large castings often require multiple weld repairs to remove entrapped slag, shrinkage porosity, hot tears, or other common defects. These defects are often not recorded for the eventual owner to track/inspect in the future. Additionally, volumetric inspection of castings is almost impossible with today's ultrasonic inspection technologies. Therefore, cast products can present their own set of issues for nuclear applications.
- For large forgings, differences in microstructures are commonly observed near tight radii or other major dimensional changes in a component. Such differences often lead to poor inspectabilty and, on occasion, can impede penetration of sound waves across the area of concern during ultrasonic inspection.
- Similarly, extruded or drawn components can exhibit poor inspectability along preferential directions.

It is for these reasons that alternative manufacturing methodologies such as PM-HIP are being explored by the Electric Power Research Institute (EPRI) [1, 2, 3].

PRODUCTION OF NEAR-NET-SHAPED COMPONENTS

The PM-HIP process consists of a number of steps, including the following (see Figure 1):

1. Powder atomization
2. Modeling of the capsule (can) tooling to allow for shrinkage
3. Fabrication of the capsule
4. Filling of the capsule with powder through fill stems
5. Vibration of the capsule ensuring powder is evenly dispersed
6. Vacuum degassing to remove trapped gases within the capsule
7. Crimping of the fill stems and welding them shut to maintain the capsule under pressure
8. HIP at high temperature and pressure to consolidated the powder

Several of the key steps in the production process are described in more detail in the following sections.

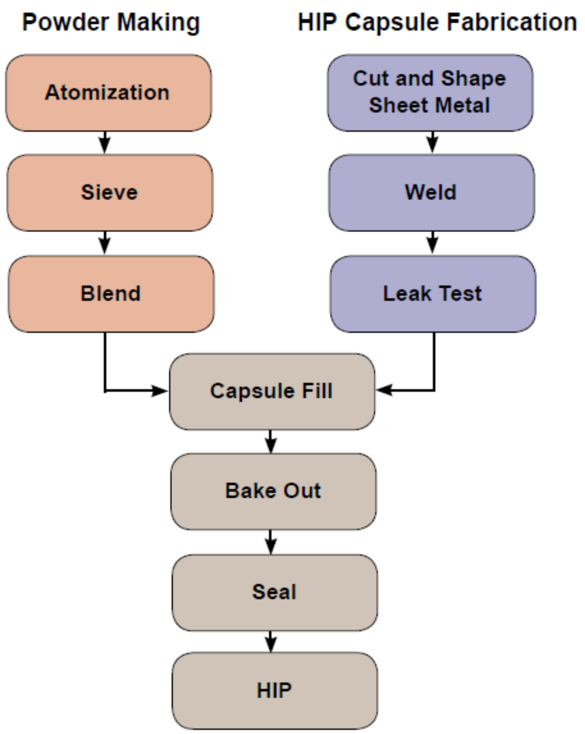

Figure 1. The PM-HIP process involves multiple steps including powder production and blending, capsule fabrication, filling, and HIP
Used with permission from Steve Mashl, Z-Met Corporation

Powder Atomization

Powder atomization is used to produce alloy powders that are then sieved to specific diameters and re-blended to develop specific packing densities for uniform consolidation. Atomization involves induction melting of specific raw alloy products to generate the desired final powder chemistry. After this is achieved, the molten metal is flowed into a tundish and released through a nozzle, as shown in Figure 2. The metal flows out the bottom of the nozzle into a nitrogen or argon environment wherein it rapidly solidifies into various diameters of powders. After the melt has been fully atomized, the powders are collected from the bottom of the atomizer and placed into containers for storage under controlled conditions. The powder is then sieved and re-blended as described previously.

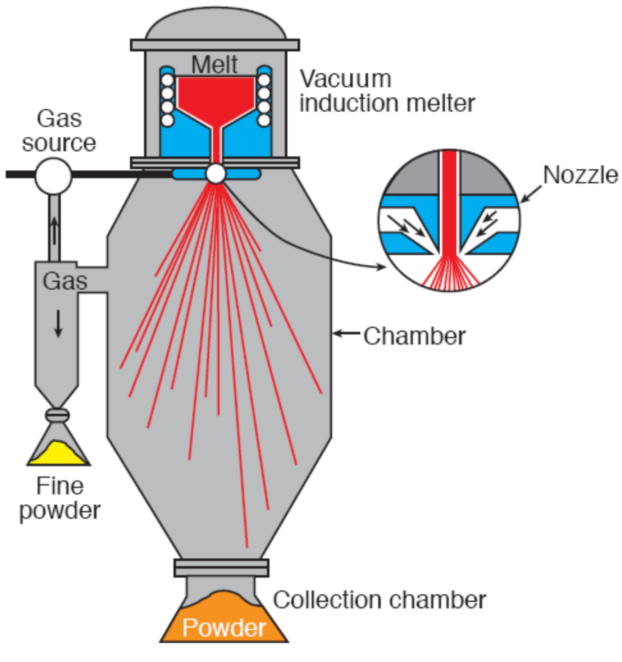

Figure 2. Powder atomization involves induction melting of an alloy, flowing of the melt through a tundish/nozzle, and rapid powder solidification in an inert environment

Canning and Filling of the Capsule

Capsule fabrication is performed following modeling of the capsule tooling to accommodate for movement and shrinkage of the capsule during HIP consolidation (see more on modeling in the following sections). Fabrication commonly involves metal forming of 0.25 in. (6.35 mm) thick carbon steel sheet metal into various geometries that are then welded together to achieve the desired final capsule geometry. After the final geometry is achieved, the capsule is cleaned and fill stems are added. Powder is then introduced through the fill stems, and the entire capsule is vibrated to evenly disperse powders throughout the entire capsule. The capsule is degassed by introducing a vacuum for several hours and then sealed shut by crimping the valve stems and welding them shut. At this point, the filled capsule is ready for HIP consolidation.

Powder Consolidation by HIP

Powders are consolidated by PM-HIP at high temperatures and very high pressures in a HIP vessel. HIP operational temperatures and pressures depend on the alloy powder that is being consolidated. For common nuclear alloys (for example, austenitic stainless steels, low-alloy steels, and nickel-based alloys), HIP temperatures often range from 1900°F to 2200°F (1040° to 1200°C), whereas HIP pressures are often on the order of 15,000–20,000 psi (100–140 MPa). Figure 3 provides an example of a large 63-in. (1600-mm) diameter HIP furnace. Near-net-shaped components can be readily achieved using the process described previously.

Figure 3. A 63-in. (1600-mm) diameter HIP unit
Used with permission from Stack Metallurgical

IMPROVED INSPECTION CHARACTERISTICS

As mentioned previously, one of the key attributes of the PM-HIP technology is the ability to produce near-net-shaped components that are readily inspectable. Poor inspection qualities of castings and, in some cases, forgings invite the need for improved manufacturing methods that can provide better inspection characteristics during fabrication and through component life. Upon consolidation of a powder into a PM-HIP component, the component develops a very homogenous microstructure across the entire part. This homogenous structure renders the component highly inspectable across any direction wherein ultrasonic sound can be directed through the part (see Figure 4). Changes in microstructure produced by other processes often impede the ability to push sound through a part; however, this is not the case with PM-HIP. Uniformity in the microstructure along all directions produces a clear path wherein to transmit ultrasonic sound while also producing isotropic mechanical properties.

Figure 4. Homogeneous microstructures in PM-HIP components promote improve inspection characteristics [1]

ELIMINATION OF WELDS

Another attribute of PM-HIP that cannot be overlooked is the ability to eliminate certain weldments when assembling components. PM-HIP components are produced to the geometry of the capsule (can) that is generated to contain the powder prior to consolidation. Complex components can be generated without the need for multiple welds during assembly that are required using the traditional aforementioned technologies. With PM-HIP, the entire component can be produced as one assembly. In doing so, expensive (and time-consuming) inspections may be eliminated altogether.

RAPID PRODUCTION OF COMPONENTS

Production of a component through forging can often take two to five years depending on the size/complexity of the part, the experience of the manufacturer in producing the part, and the backlog of the producer. One of the key advantages offered with PM-HIP is the ability to rapidly produce large components. This is particularly true if detailed model and capsule designs have already been generated. If the capsule has been designed, components can often be produced in as few as six to 12 weeks, depending on their complexity and size. If the model and capsule designs are not available, an additional four to eight weeks can be added to the schedule. Realistically, PM-HIP components can be produced in less than 20 weeks, which makes the overall process very attractive when compared with conventional manufacturing technologies.

TECHNOLOGY READINESS

Preventive maintenance components similar in size to those used in nuclear service have been used by the offshore oil and gas industry for more than two decades for major components such as manifolds, valves, tees, and wyes. These components are exposed to highly corrosive conditions (ocean water) and are commonly found at depths of hundreds to several thousand feet. Other industries, such as automotive, aerospace, food processing, and aircraft industries, commonly use PM-HIP parts, though many of their parts are much smaller than those being

Key Benefits of PM-HIP

- Near-net-shaped feature enables reduced machining and material volume required
- Homogeneous microstructure promotes superior inspection characteristics
- Elimination of certain welds
- Shortened delivery time
- Ideal for multiple penetration applications

considered for nuclear applications. Therefore, other industries have quite a bit of experience with the technology.

Acceptance of the technology for nuclear applications has been slow, however, because utility design control documents often dictate the manufacturing methods of components. Only recently have utilities/original equipment manufacturers realized that PM-HIP is a viable technology for production of major components. EPRI believes that many organizations will embrace PM-HIP for production of pressure-retaining components during the next few years and that the technology will be readily applied for SMR and AR applications.

EMERGING PM-HIP TECHNOLOGIES

SMR Manufacture and Fabrication

Current EPRI Work

Spearheading a large U.S. Department of Energy (US-DOE) project on SMR Manufacture and Fabrication (DE-NE0008629) wherein large components of upper and lower reactor assemblies are being manufactured at two-thirds scale using PM-HIP and then assembled with electron beam welding.

To reduce manufacturing and fabrication costs, equipment manufacturers must begin looking at new, more efficient technologies for producing reactor pressure vessels, steam generators, pressurizers, and so forth. EPRI and the United Kingdom-based Nuclear Advanced Manufacturing Research Centre are leading a project to demonstrate several new technologies that can be applied to these components. These technologies include PM-HIP, electron beam welding, diode laser cladding, additive manufacturing, and advanced machining methods. The goals of the project include the following:

- Accelerate the deployment of SMRs
- Develop/demonstrate new methods of manufacturing/fabrication to reduce the production time of a SMR to less than 12 months
- Eliminate 40% of the costs of a SMR vessel

Early results of the project have been reported in EPRI reports 3002015814 and 3002019335.

Major components being generated by PM-HIP in the project include the upper and lower reactor heads, steam plenum, and steam plenum access covers representative of those to be used for the NuScale Power reactor pressure vessel (see Figure 5). Today's PM-HIP technology is limited by the size of HIP vessels worldwide. As a result, many of the components are being produced in half sections and then assembled with electron beam welding. The project looks to demonstrate PM-HIP capabilities that will one day lead to much larger HIP vessels capable of producing large SMR and AR components.

Figure 5. A SMR vessel head was produced at 44% scale using A508, Class 1, Grade 3 low-alloy steel powder (The head weighed 3650 lb (1650 kg), contained a total of 27 penetrations, and was produced as one solid monolithic structure. Note: the white dots were used as part of the laser dimensioning process.) [2]

Modeling Methodologies for Rapid Prediction of Capsule/Can Geometry and Shrinkage

Current EPRI Work

Developing modeling capabilities and software to address prediction of capsule/can shrinkage that occurs during HIP of the component.

One of the key challenges to the application of overall PM-HIP process cycle is the availability of modeling tools that can predict geometrical changes that occur during consolidation of the capsule/can. Geometrical modeling is used to define the tooling required for capsule fabrication. Finite element modeling (FEM) is often coupled with discrete element modeling

(DEM) methodologies to predict overall powder shrinkage and movement during HIP application. Shrinkage values can be up to 30%, depending on the powder packing density and other features; therefore, prediction of the shrinkage is not a trivial exercise. It often takes days of computational power to arrive at the final capsule tool design.

EPRI and Oregon State University are exploring a new approach aimed at providing a reliable simulation of the HIP process while reducing the overall time and computational power required to arrive at a final tool design. The proposed application still links FEM and DEM methods but then uses an iterative approach to lessen the raw computing power required overall. The goal of the project is to reduce the computing time to less than a day, while allowing design engineers or PM-HIP engineering teams to use plug-and-play software to predict tooling geometry and shrinkage. The software would work with commercially available finite element analysis packages such as ANSYS or ABAQUS. The uniqueness of the approach lies in the creation of a more automated design process through minimizing input required from the user, while offering a more realistic and accurate capture of filling and HIP densification phenomena.

ATLAS—Advanced Technology for Large-Scale HIP Components

Current Industry Work
Industry collaboration to install a 140-in. (3556-mm) diameter vessel capable of producing major nuclear components such as a SMR vessel head or steam plenum.

The production of large nuclear components using PM-HIP will require a much larger HIP capability than presently exists today. The largest HIP vessel in the United States and Europe is on the order of 66 in. (1675 mm), whereas the world's largest HIP vessel (81 in. [2060 mm]) is in Japan. Many nuclear components are of sufficient size that they can be produced in the current vessels; however, many cannot. EPRI is working with industry to bring Advanced Technology for Large-Scale (ATLAS) HIP—forward to enable production of very large components, up to 120 in. (3048 mm) in diameter. The ATLAS HIP vessel will have a working inner diameter on the order of 140 in. (3556 mm) and will allow for shrinkage of the component during consolidation. EPRI has organized two workshops to bring potential collaborating organizations together to establish where ATLAS could be built and what mechanism might be used to fund the system and to define the size/capabilities/cycles required by industry. It is anticipated that partners will be established in the near future.

NEXT STEPS/ONGOING EPRI WORK

Other activities are being addressed in EPRI's PM-HIP research, including the following:

- The use of vacuum annealing of low-alloy steel powders to achieve a pristine powder, free of contaminants such as oxygen, water vapor, or other gases that can be trapped in a large canister/can
- Development of a data package and an ASME Code Case for A508 low-alloy steel components produced by PM-HIP
- Assessment of the irradiation effects on PM-HIP alloys in both the welded and unwelded conditions

It is believed that PM-HIP will be used extensively over the next few decades to produce pressure retaining components for SMR and AR applications, particularly for complex components. Furthermore, the technology will be employed to produce reactor internals and in applications where certain welds can be eliminated.

KEY REFERENCES

1. *Program on Technology Innovation: Manufacture of Large Nuclear and Fossil Components Using Powder Metallurgy and Hot Isostatic Processing Technologies*. EPRI, Palo Alto, CA: 2012. 1025491.
2. *Small Modular Reactor Vessel Manufacture and Fabrication: Phase 1—Progress*. DOE and EPRI, Palo Alto, CA: 2019. 3002015814.
3. *Small Modular Reactor Vessel Manufacture and Fabrication: Phase 1—Progress (Year 2)*. DOE and EPRI, Palo Alto, CA: 2020. 3002019335.

4. D. Gandy, et al, Innovative Manufacturing Process for Nuclear Power Plant Components via Power Metallurgy-HIP, DOE Final Report, DE-NE0000544, August 2016.

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