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ADDITIVE MANUFACTURED, NET SHAPE POWDER METALLURGY CANS FOR VALVES USED IN ENERGY PRODUCTION

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OAK RIDGE NATIONAL LABORATORY
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Energy and Environmental Sciences Directorate
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Additively Manufactured, Net Shape Powder Metallurgy Cans for Valves Used in Energy Production

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ORNL would like to acknowledge the leadership of EPRI in pulling together the extensive team and managing the execution of the project. In addition, ORNL would like to acknowledge the other contributions of the team members associated with this project. Quintus provided time, access, expertise, and labor of their hydro forming capabilities to evaluate both conventional and additively manufactured tools through this process. Crane ChemPharma Energy provided guidance and information on valve geometries. Carpenter Powder Products was involved with the team providing information on powder processing as it pertains to the canning and hot isostatic pressing of powder. on providing powder and knowledge as it pertains to powder supply for hot isostatic pressing; they also provided powder for the test trials by the industrial team. Bodycote provided guidance on hot isostatic pressing and can requirements. They were also responsible for the hot isostatic pressing of the test valve performed by the industrial team.

ABSTRACT

Additive manufacturing (AM) has the potential to enable a paradigm shift in fabricating complex net shape components with yields over 90%, significantly increasing productivity, decreasing energy consumption during manufacturing and improving downstream energy efficiency. ORNL has developed a technology for producing large-scale additively manufactured polymer matrix composite components at deposition rates on the order of 100 lbs. per hour. This project utilized tools, dies and molds made from this technology to enable the net shape forming of cans for the powder metallurgy (PM) manufacturing of valves used in energy production plants. This approach has the potential to develop affordable valves with superior performance to castings. It will also lead to increased strength values, decreased wall thickness size, and the potential for higher yields (less machining). This project is critical for evaluating new methodologies for the fabrication of additively manufactured tooling, molds and dies that could be used across multiple industries.

Figure 1: Typical Valve Body

In the first phase of this project, a new methodology of creating a Powder Metallurgy and Hot Isostatic Pressing (PM-HIP) container by hydroforming sheet metal over additively manufactured (AM) dies was evaluated. The goal in this stage of development was to evaluate some of the new polymer matrix composite materials designed for deposition on large scale additive manufacturing systems as candidates for hydroforming steel and aluminum sheet to make thin gauge net shape components. In order to meet this objective, most research was performed on subscale tools in order to evaluate the processing pressures, material options, and gauge thicknesses most relevant to this approach. In addition, full scale AM tools (30% over final component geometry) were produced to demonstrate scalability, but were not used in testing. The first phase of this project has proven this concept has merit, but future studies are required to address minor tool failures that occurred in phase one due to geometry, cost of the process over other techniques, and demonstration of a full-scale tool that could then be used in (HIP). Lastly, this project provides the PM community a new approach in using hydroforming for the manufacturing of cans, a process that was not highly utilized for this purpose previously.

1. ADDITIVELY MANUFACTURED, NET SHAPE POWDER METALLURGY CANS FOR VALVES USED IN ENERGY PRODUCTION

This phase 1 technical collaboration project (MDF-TC-2014-047) began on December 5, 2014 and was completed December 5, 2017. The collaboration partner, Electric Power Research Institute (EPRI), is a large, independent, nonprofit organization for public interest, energy savings, and environmental research. The project successfully evaluated the use of an additively manufactured tool to hydroform thin gauge sheet into net shapes that could be used in can production for hot isostatic pressing with minimal joining.

1.1 BACKGROUND

The manufacturing methods used for the production of valves (gate, globe, etc.) and pump housings for the energy market has essentially remained unchanged for over 50 years. Small, medium and large cast valves are produced via sand casting methods which make use of a reverse sand mold into which molten metal is poured and solidified. Valve casting methods often result in substantial repair and rework to the final component to address casting defects such as laps, segregation, hot tears, voids, pockets, secondary phases, intermetallic phases, etc. It is not uncommon for repairs and rework to comprise 20-50% of the overall cost.

Another manufacturing method used for selected valves is forging. Forging produces a very high-quality component, but often requires considerable machining to achieve the final component dimensions. Removal of large amounts of material can drive the overall cost of the final valve product upward in terms of labor and in excess volume of materials.

More recently, another valve manufacturing method has begun to emerge. EPRI, in conjunction with Carpenter Powder Technologies, a powder producer, and number of valve manufacturers, has produced several valve bodies via PM-HIP resulting in acceptance of two American Society of Mechanical Engineers (ASME) Code Cases (Grade 91 steel and 316L stainless steel). The technology produces a very high-quality product with mechanical properties that easily exceed cast products and often equate to or exceed forged valve products. PM-HIP-produced valves demonstrate good inspectability, no welding repair requirements, high toughness, and the ability to be produced in near-net shaped conditions. Manufacture of a valve from PM-HIP requires several steps:

Selection and design of the valve geometry
Powder production
Fabrication of a tool and die geometry used to fabricate the can (capsule)
Development of a valve can (capsule) to near net shape to contain the powder
Degassing and sealing of the can/capsule
Powder consolidation and HIP

Of these six steps, those which have the greatest potential to drive the overall production costs downward to make PM-HIP more cost competitive are steps 3 and 4. Items 1, 2, 5, and 6 are essentially fixed costs. It is believed that the cost of steps 3 and 4 can comprise 25-45% of the overall PM-HIP process costs. Thus, development and demonstration of new technologies to drive these costs downward are paramount to the wide-spread use of the PM-HIP manufacturing technology for valve applications.

The objective of this project was to develop an affordable approach to making simple net shape valves via PM-HIP to be used in energy production plants including coal, nuclear, chemical, petroleum, etc. by evaluating both new can production methodologies that include hydroforming of net shape components and evaluating the potential for additively manufactured tools to be used in this process. The consolidation of powder using cans and HIP has been evaluated for the production of valves (References 1-7). Current practices of "stick building" cans/capsules require considerable fabrication and welding, along with the production of dies, tooling or mandrels. Together, these represent one of the major costs associated with the PM-HIP manufacture of valves or other large power generation components.

Two approaches were considered in the project to significantly reduce the overall production cost of cans/capsules: 1) Large-scale polymer AM enables rapid fabrication of limited production die and tooling critical to enabling the forming of cans/capsules. This approach is strictly aimed at the development of the production die and tooling preform which will be used to fabricate cans/capsules 2) Flexforming, a variation of the hydroforming technology developed by Quintus Technologies, will be considered to directly manufacture the cans/capsules on a half shell. The cans/capsules can then be welded together to form the valve geometry.

1.2 TECHNICAL RESULTS

An 8-inch, 2500lb. gate valve design was selected for the project. The team had planned to design and manufacture both Grade 91 and 316L stainless steel (SS) valves using hydroforming techniques to fabricate the can. The team was comprised of five companies: ORNL to fabricate the AM tools, EPRI to manage the project and evaluate the methodology for future valve body production for use in power plants, Quintus Technologies to evaluate their Flexform process (a hydroforming technology), Crane to provide the relevant 8-inch valve body design, and BodyCote to construct the can, fill it with powder and perform HIP'ing to consolidate the valve body.

Four subtasks were identified for the first phase of this project:

Task 1 – Can/Capsule Inside Diameter (ID) Technical Feasibility Assessment. Led by ORNL, with input from Crane and Quintus.

Task 2—Develop ID Can/Capsule Inside Dimensions for hydroforming. Led by Bodycote, with input from Crane.

Task 3—Fabricate Final 8-inch ID Can/Capsule via hydroforming. Led by Quintus Technologies.

Task 4—Assess Outer Diameter (OD) Can/Capsule Dimensions and/or Fabrication Method and Manufacture 8-inch Valve Bodies. Led by Bodycote.

During Task 1, ORNL found the original additively manufactured tool material, acrylonitrile butadiene styrene + 20% carbon fiber (ABS +20% CF), to be insufficient for the given pressures required to form the can half shell. Research in Task 1 was directed towards evaluating a larger range of tool materials, i.e. Polyphenylene sulfide + 50% carbon fiber (i.e. (PPS+50% CF), unreinforced ABS, and ULTEM, a high temperature thermoplastic, using multiple blank/sheet materials (aluminum and steel) within a large range of pressures (2 to 80 MPa) on subscale versions of both male and female tools. In parallel, the team continued to evaluate hydroforming for can production using a cast thermoset polymer tool, Bakelite or polyoxybenzylmethylenglycolanhydride. In order to effectively capture the activities of this project, the technical results have been described in 3 subsections. The first subsection (1.2.1) will describe the preliminary experiments, the second subsection will discuss the results of the increased scope of materials evaluated using subscale AM tools, and the third subsection will briefly discuss the activities of the industrial partners led by EPRI to evaluate hydroforming for can production using the thermoset tool.

1.2.1 Preliminary Experimental Evaluation

This subtask used an existing 8-inch diameter valve dimensional information to generate a male die/mold with the intent to create a hydroformed can/capsule. ORNL printed two tools; one tool at true scale and one tool at 30% larger than scale, on a Big Area Additive Manufacturing system manufactures by Cincinnati, Inc. (BAAM-CI) using ABS with 20%CF, shown in figure 2 and figure 3, respectively.

Figure 2: True scale 8-inch diameter valve internal tool.

The 30% larger tool represented the estimated size allowing for full consolidation of the powder during the HIP cycle.

Figure 3*:* 8-inch diameter valve internal tool at 30% above scale.

The tool was machined; defects from bead to bead interfaces are visible, but overall tool condition was sufficient for hydro forming as can be seen in Figure 3.

Prior to shipping the tool to Quintus for hydroforming, the team decided to fabricate small sample sections that could demonstrate whether the tool would survive at the required pressures; these tests could be performed quickly since time on smaller hydroforming equipment was available. The test specimen was a prismatic geometry with a radius removed from the top plane, as can be seen in figures 4 through 6. Three samples were fabricated and sent to Quintus with different fill densities, or different hatch spacings, in the web of the tool. Fill densities are determined by controlling the centerline distance between individual extruded beads. The purpose for testing different fill densities is to evaluate if lower fill densities in the web, or center section, could be used with benefits of a lighter tool, less material being used, and faster time to completing deposition, or if fully dense material is required in order to be capable of performing under the high pressures.

Quintus performed hydroforming tests on the three samples using Aluminum 1050. The densest sample was tested with a soft steel, DC04, at higher pressures. All sheets had a gauge thicknesses of 1mm. The two lower density builds survived 2 MPa, but failed at 4 MPa.

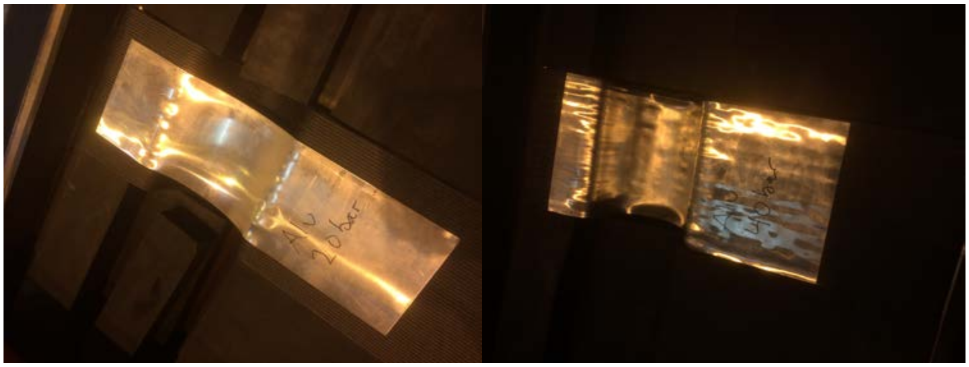

Figure 4: The low fill density tool tested at 2MPa (left) and 4 MPa (right) using Al 1050 sheet.

Figure 5: Failure of the low fill density specimen at 4 MPa.

The higher density fill tool survived at 4 MPa, but failed at 6 MPa when being tested with the steel sheet.

Figure 6: High fill density specimen tested at 6 MPa testing steel sheet (left) with the resulting failure of the specimen (right)

The failure at higher pressures of the high-density fill indicated that the AM ABS fiber reinforced material may not be compatible for this application. ORNL efforts were redirected towards investigating the use of a new, high temperature thermoplastic, PPS with 50% CF material printed on the BAAM-CI, while also investigating tools fabricated on a Stratasys Fortus system where smaller bead diameters would enable a higher filled/density tool (discussed in 1.2.2). Subscale samples would be tested on a hydroforming machine located at the ORNL Manufacturing Demonstration Facility (MDF). In order to complete the project, the team would in parallel use a cast thermoset to evaluate hydroforming as a means of fabricating PM can half shells for HIP (discussed in 1.2.3).

1.2.2 Materials Evaluation for Hydro Forming Tools

ORNL additively manufactured six additional tools for evaluation. A male and female subscale tool at 10% scale was printed for unreinforced ABS, unreinforced ULTEM, and PPS+50%CF. The two unreinforced materials were chosen to see if a fully dense print using a Fortus 900MC with a much finer resolution would improve the performance at higher pressures. A PPS+50% CF tool was printed on the BAAM-CI system and then machined to its final shape with the idea that this material was engineered to take much higher pressures than the previous ABS reinforced material. Hydroforming cycles were performed on a Beckwood Triform 16-5BD press at ORNL. Aluminum and steel sheet, or "blanks", from 0.75 to 2mm were tested (see table 1 for specific gauge thicknesses). The sheets of metal were cut into 20cm x 30cm rectangles. A grid pattern was drawn on all of the rectangular blanks prior to hydroforming to track deformation and to assist in the design of an optimized blank shape. Using the grid pattern and geometry methods, an optimized blank shape was made. The shape was then cut out of steel sheet metal that was 0.76mm, 1.52mm, and 1.91mm thick, respectively.

Table 1.

Metals	**Sheet Thicknesses (mm)**		
Aluminum	0.81	1.60	2.03
Steel	0.76	1.52	1.91

Most of the blanks were formed over several hydroforming cycles of steadily increasing pressure. After each cycle, the blank was inspected for thinning, tearing, wrinkling, spring-back and accuracy of the die shape. In addition, the die was inspected for signs of wear, cracking, noticeable deformation, and total failure. Die wear was acerbated due to occasional crimping of a blank and the difficulties in removing the blank from the die, creating additional superficial scratches. Blanks were drawn until the maximum pressure was achieved or until a blank failed through tearing.

Most cans for HIP'ing would be steel; however, ORNL also tested aluminum sheet to evaluate forming of a softer material. Many of the aluminum blanks tore prior to hitting maximum pressures as shown in Figure 7. Examples include a 0.81mm thick aluminum blank hydroformed on a male die that failed at 13.79 MPa (left), and another 0.81mm thick aluminum blank hydroformed on a female die that had catastrophic failure at 3.4 MPa (right).

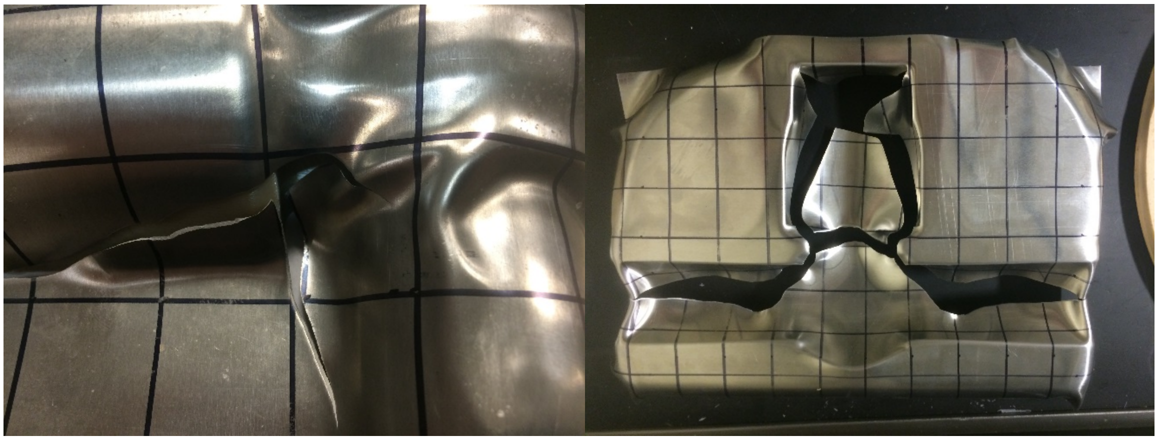

Figure 7: Aluminum sheet failure on male (left) and female (right) AM tools.

Overall, the steel blanks formed well on the AM tools with minimal tearing and desirable shape accuracy. The occasional steel blank tear was minimal and contained no sharp edges. Figure 8 (left) provides an example of the tear on a steel 0.76mm thick blank using a male tool. ORNL was successful in pressing a near net shape 0.76mm thick steel blank pressed at 34.5 MPa on an ULTEM tool. The final shape was successful obtained by initiating forming on a male die at lower pressure to obtain a general shape and then completing the process on a female die up to the 34.5 MPa, as seen in Figure 8 (right).

Figure 8: Failed (left) and successful (right) hydroformed net shapes.

Steel blanks at each of the thickness (0.76, 1.52, and 2.01mm) were successfully formed into the subscale can net shape. The thinner blanks formed a more accurate shape at these pressures; however, the blanks were more prone to thinning and tearing. The 0.76mm steel blank was only able to be formed at the highest pressure of the hydroforming press by using the combination of positive and negative dies. Thicker steel blanks, 0.060’’ and 0.075’’, were able to be pressed at the highest pressure of the press without tearing on both the positive and negative dies individually.

Based on the results of using the grid pattern, a pre-cut blank was fabricated. Without excess material, a blank will be less inclined to tear and wrinkle. This blank shape can be seen in figure 9.

Figure 9: Optimized pre- shape of blank based on previous grid patterns.

The overall goal of this project was to evaluate the opportunity to use AM tools for hydroforming steel cans. Each of the subscale tools survived the multiple cycles performed up to 35 MPa, well above the preliminary tests of the reinforced ABS material. However, the repeated cycles of hydroforming did have an effect on the softer ABS and ULTEM tools exhibiting deformation at sharp edges. Examples of the deformation can be viewed in figure 10. Overall, the negative, or female die, experienced more deformation than the male die.

Figure 10: Female ABS die (left), and male ULTEM die (right), both exhibiting minimal deformation after repeated use at higher pressures.

Due to the success of hydroforming the PPS + 50% CF tools with no visible deformation, the male and female tools were sent to Quintus where test pressures could be evaluated from 10 MPa to 80 MPa (maximum pressure approximately twice the capability at ORNL). Figure 11 is an image of the male and female dies that were sent.

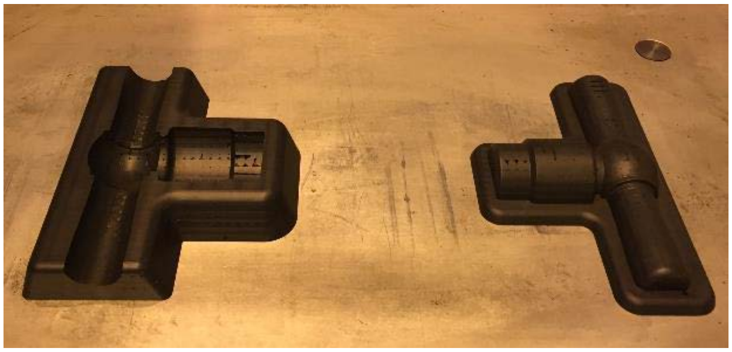

Figure 11. Female and male PPS+50% CF tools.

Quintus performed pre-trials with aluminum 6016-T4 sheet at 15 MPa. The steps through hydroforming can be observed in figure 12, including placement of the blanks on the tools (left), the placement of the rubber cover to avoid accidental puncture of the hydroforming bladder (center), and the final outcome of the hydro forming trial right. As can be observed, the blank on the female tool tore while the blank on the male tool experienced some wrinkling. However, both tools were in good condition after the pretrial experiment.

Figure 12. Female and male PPS+50% CF tools with blanks (left), placement of the rubber mat (center), and final results (right).

After completing the pre-trials, Quintus tested the female tool using DC04 steel blanks of 1mm and 1.5mm thicknesses at pressures of 10, 30, 50, and 80 MPa. Quintus noted that the tool generally had a good surface, but some areas had noticeable voids that were a result of bead to bead defects from the deposition process. During the trials of the female tool with a 1mm thick blank, the blank ruptured at 15 MPa. The blank tested at 80 MPa formed to the tool picking up the defects of the tool surface. These results can be observed in figure 13.

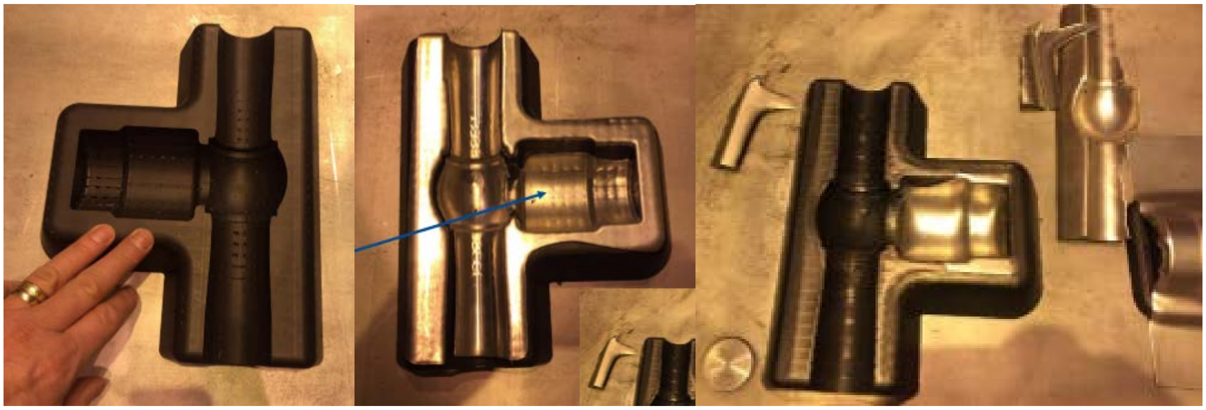

Figure 13. Female cavity/tool (left), results of 80 MPa test (center, with arrows to surface defects), and results of 15 MPa test (right) with 1mm blank thickness.

The tool was then tested at 80 MPa with a 1.5mm thick blank. The surface defects were not visible with the thicker sheet and the material didn't crack. However, less forming resulted into the narrow spaces. Overall, the tool survived the high pressures; however, there was some damage of the tool at sharp corners. The final thick blank results and condition of the final tool can be observed in figure 14.

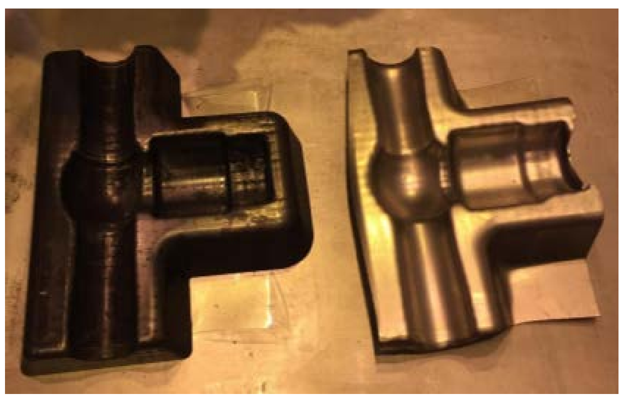

Figure 14. The female cavity/tool after trials (left) with the formed 1.5mm/0.060" blank (right).

Similar trials were performed on the male tool using a 1mm thick blank. Overall, similar findings were seen with the male tool as with the female tool. At lower pressures (30 MPa), the blank did not form well around the tool, but also did not rupture. At the higher pressures the blank formed to the tool; some crimping was also observed. Overall, the tool survived; however, once again, there was some damage to the sharpest corners. The results of the male tool can be observed in figure 15.

Figure 15. The male additively manufactured tool (left), tested with a 1mm blank at 30 MPa (center), and at 80 MPa (right).

Quintus made some overall observations of the AM tools. The geometry of the tools could have been better optimized for hydroforming; this includes slight modification of sharp corners, adding 10 to 15mm additional height of the cavity tool (female tool) to allow for a gentle draw radius, developing a draw holder surface around the male tool, and providing a means for air evacuation in the tool. The tools had a generally good, smooth surface, but defects related to bead geometry can cause defects to the formed part at thinner gauge blanks. Overall, the tools performed extremely well, even at high pressures, and could be considered for making can half shells for HIP'ing. However, the project could have had even better results had the tools been optimized for hydroforming. Future efforts could benefit from these lessons learned as the tool would be scaled appropriately for a full-size valve body.

1.2.3 Hydro Forming of Can Net Shapes Using Cast Ceramic Tools

Bodycote worked with Crane to develop ID Can/Capsule dimensions accommodating for shrinkage. It was important to establish accurate control of the ID dimensions. Therefore, this subtask did not focus on the OD can/capsule. Quintus then used a wood tool to hydroform the internal structure of the can/capsule using the dimensions established by Bodycote and Crane. Once the ID can/capsule had been successfully generated, Bodycote worked with the team to construct the outside diameter can. Bodycote then joined the OD and ID together, filled the can with powder, evacuated the can of gas, sealed it, and HIP'ed an 8-inch Grade 91 and 316L SS valve body. The results of this portion of the project exhibited that hydroforming can be used for fabricating cans.

1.3 IMPACTS

This phase has demonstrated the feasibility of hydroforming sheet metal into shapes usable in a PM-HIP container on a small-scale tools fabricated from AM. Hydroforming was validated as a methodology for can fabrication; process estimates will need to be generated in future efforts to determine when this approach is economical (most likely on more complex cans) and when conventional practices are more attractive to fully understand the impact of the technology.

1.4 CONCLUSIONS

The tests have demonstrated that hydroforming sheet metal on an AM tool into a container shape is feasible. Material selection is important for success. In this project, PPS + 50% CF was found to be able to survive at a large range of practical pressures (up to 80 MPa). However, further studies with this material should be performed on tool geometries that are optimized for hydroforming.

2. ELECTRIC POWER RESEARCH INSTITUTE, INC. BACKGROUND

The Electric Power Research Institute, Inc. conducts research, development and demonstration (RD&D) relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together scientists and engineers as well as experts from academia and the industry to help address challenges in electricity. Their work spans nearly every area of electricity generation, delivery and use, management and environmental responsibility, and provides both short- and long-term solutions in these research areas for the electricity industry, its customers and society. The depth and breadth of EPRI's work is outlined in their 2017 Research Portfolio.