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Hot Isostatic Pressing: Methods and Procedures

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14. ABSTRACT
The experimental procedures detailed herein delineate a comprehensive methodology for the preparation and assembly of hot isostatic pressing (HIP) cans. The procedure encompasses detailed steps from the acquisition of materials (including stainless steel tubing, end caps, stems, and other essential components) to the fabrication and sealing of the cans. Noteworthy equipment (e.g., the vessel leak checker, stem crimping vise, bakeout furnace, and argon atmosphere glovebox) play pivotal roles in ensuring the integrity and quality of the HIP cans. Welding and sealing procedures demand precision and attention to detail to ensure hermetic sealing of the vessels. Subsequent bakeout processes involve controlled heating and vacuum conditions to remove contaminants and moisture effectively. Stem crimping and sealing procedures culminate in the final closure of the vessels, safeguarding the encapsulated materials for subsequent processing steps.

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1. Introduction

Amidst a growing demand for enhanced performance capabilities, the US Army is actively pursuing the development of novel bulk nanocrystalline metals and alloys that exhibit superior characteristics and are adaptable to a diverse array of operational settings. To address this imperative, a comprehensive program has been meticulously crafted to focus the following key objectives:

- Processing and consolidating nonequilibrium and metastable particulate materials.
- Exploring thermodynamic and kinetic principles governing grain growth and microstructural stability.
- Investigating the fundamental physics of deformation in nanostructured metallic alloys under extreme conditions and encompassing temperature and strain rate variations.
- Implementing advanced characterization techniques, such as aberration-corrected transmission and scanning electron microscopy, in tandem with 3D atom probe tomography.
- Engaging in computational materials simulation and design.
- Pioneering efforts toward the commercialization of stabilized bulk nanocrystalline alloys.

The collective endeavor spanning the past decade has culminated in the successful realization of large-scale stabilized bulk nanocrystalline/nanostructured materials and is propelled by advancements in fundamental understanding and associated engineering and processing technologies. These strides have facilitated the conduct of conventional full-scale mechanical testing and characterization—ranging from tension, fatigue, and creep to shock and ballistic evaluations—previously deemed unattainable for this class of materials.

More recently, the nanocrystalline metals group at the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) recently introduced the acronym "NCPRO," the emblem of which is depicted in Fig. 1. This emblem symbolizes a network of labs strategically designed for collaborative advancement in nanocrystalline powder technology. This collaborative framework aims to progress from proof-of-concept ideas to pilot-scale and premanufacturing stages, fostering the production of designed parts, expertise development, and the establishment of manufacturing science for scaled-up processing. The foundational elements of NCPRO, collectively known as its "core components," encompass fundamental aspects contributing to its structure, function, and identity. Crucially, NCPRO facilitates internal collaboration with other ARL divisions and external partnerships with research institutes and industrial counterparts through commercialization and transition processes.

Fig. 1 NCPRO logo

2. Hot Isostatic Pressing (HIP)

HIP is a sophisticated manufacturing process used across various industries to enhance the material properties of metallic, ceramic, and composite components. Employing a combination of elevated temperature and pressure, HIP subjects materials to uniform conditions, resulting in densification, consolidation, and the elimination of defects from powder metallurgical (PM) parts.

At its core, HIP involves placing a PM component or a powdered material within a sealed containment vessel, typically made of steel or another robust material. The vessel is then evacuated of air, degassed, and sealed to create a hermetic environment and prevent oxidation during the process.

The HIP process unfolds in a specialized chamber equipped with heating elements and a pressure vessel. The component, contained within the sealed vessel, is subjected to elevated temperature and pressure simultaneously. Temperatures often reach up to 2000 °C (3632 °F), while pressures can exceed 1000 MPa (145,000 psi). These extreme conditions allow simultaneous application of heat and pressure, which are crucial for achieving optimal material properties.

The primary objective of HIP is to eliminate porosity within the material, enhancing its density and mechanical properties. Porosity, or voids within the material, can compromise structural integrity and mechanical performance. By subjecting the material to high pressure from all directions (isostatic pressure), HIP effectively compresses any existing voids and results in densification.

The HIP can, usually made of a durable material such as stainless steel, encases both the mandrel and the powder material being processed, creating a sealed environment necessary for the application of elevated temperature and pressure. This process can be time-consuming and expensive.

3. Experimental Procedures: HIP Canning Procedure

Although HIP vessels can be fabricated in different sizes and with different geometries, our process has standardized their construction, which allows them to be scaled up or down depending on requirements.

3.1 Materials List

The following components are required to fabricate HIP vessels:

- Stainless steel tubing, typically 304 stainless steel 3A tubing (20Ra MPID/32Ra MPOD-Austenitex) with a 0.065-inch wall thickness, available in diameters from 1 to 6 inches. Larger diameters may have thicker walls.
- End caps are machined from 304 stainless steel. Usually, these are machined from round stock closest to the tube size and most often purchased from McMaster-Carr.
- Stems used to evacuate sealed cans are 3/8- and 1/2-inch seamless, 304 stainless steel tubing. Normally, a 0.065-inch wall thickness is used from McMaster-Carr or other suppliers.
- The “bullets” that prevent stem weld collapse are also made from 304 stainless steel.
- Filter disks to prevent metal powders from exiting the vessel during evacuation are fabricated from 304 stainless steel wire mesh (10 µm) and made to size for each can diameter. These disks were custom-made by Ejay Filtration. Heated and dried steel wool also may be used by pressing a quantity of steel wool into a disk shape.

3.2 Vessel Parts List

The following are more detailed descriptions of geometries of the individual HIP vessel components:

- Tubes that are manufactured in varying lengths, all with 60° chamfer on both ends. Each tube must be fully deburred and cleaned before filling.
- The bottom cap is machined to be a light press fit to the diameter of tube that is being used. Each cap has a 60° chamfer that matches the chamfer on the tube. This feature is used to create an autogenous weld that seals the bottom of the vessel.
- Stems are cut to length with tubing cutters to create sharp and viable ends. Interior diameters are deburred and a 60° chamfer is added to one end of the tube. This will function as a feature for an autogenous weld to the top cap.
- The top cap has an outside diameter that is machined to be a light press into the filled tube; this diameter has a 60° chamfer identical to the one on the bottom cap for the same purpose. The top cap also has a hole in the center that allows for a slip fit of the chamfered end of the stem into the cap.
- “Bullets” are approximately 1 inch in length and are meant to slide easily in the stem. Their shape resembles a bottle shape and has rounded edges. Two grooves oriented axially on the outside diameter of the bullet are added to allow contamination to escape during the bakeout process.
- Subassemblies are shown in Fig. 2 and are as follows:
    - A “vessel” is simply a bottom cap that is welded onto a tube. Each vessel must be checked for leaks prior to being loaded with powder.
    - A “stem cap” is made from a stem that is inserted into a top cap and welded into place. Stem caps are created by first welding the side of the stem that will be to the inside of a filled vessel. The stem is positioned inside the cap with the bottom edge of the chamfer lined up with the inside of the cap. This is then welded autogenously to fix the tube in place. The stem cap is then flipped over and the stem to cap seam is welded with filler wire to complete the assembly.

Fig. 2 A variety of HIP vessels before powder loading, as well as stems and caps. The 60° chamfers can also be seen (A), and the welded ends of the HIP vessels before leak testing (B).

3.3 Major Equipment List

Each of the following pieces of equipment was designed and fabricated to perform tasks specific to our method of constructing HIP vessels. All apparatus were assembled from off-the-shelf components and custom-fabricated parts.

3.3.1 Vessel Leak Checker

The vessel leak checker (Fig. 3) is a custom-built piece of equipment that is used to check the seal of a vessel before it is loaded with powder. It consists of an Edwards RV5 vacuum pump that is mounted to a custom-designed frame made from 80/20 extruded aluminum. The top surface of the apparatus has a semisoft surface that is chemically resistant and will seal around the lip of a vessel when negative pressure is induced. The vacuum pump is connected directly to the underside of the top surface so that when the pump is turned on and a presumably sealed vessel is placed on the top, a sufficient vacuum will be achieved. The vacuum level is displayed on a digital gauge mounted on a control panel that has a master on/off switch, vacuum release, level gauge, and pump on/off switch.

Fig. 3 Vessel leak checker with HIP can during testing

3.3.2 Stem Crimping Vise

The stem crimping vise (Fig. 4) is a custom-built piece of equipment that is used to crimp and seal the stems of vessels after they have been "baked out." The system consists of two components. The first component is an adjustable-height, automotive-transmission-type rolling jack stand that has an Enerpac hand-operated hydraulic pump attached. The second piece consists of the same type of transmission jack stand, but with a custom-built anvil and crimping jaws that are actuated by an appropriate Enerpac hydraulic cylinder.

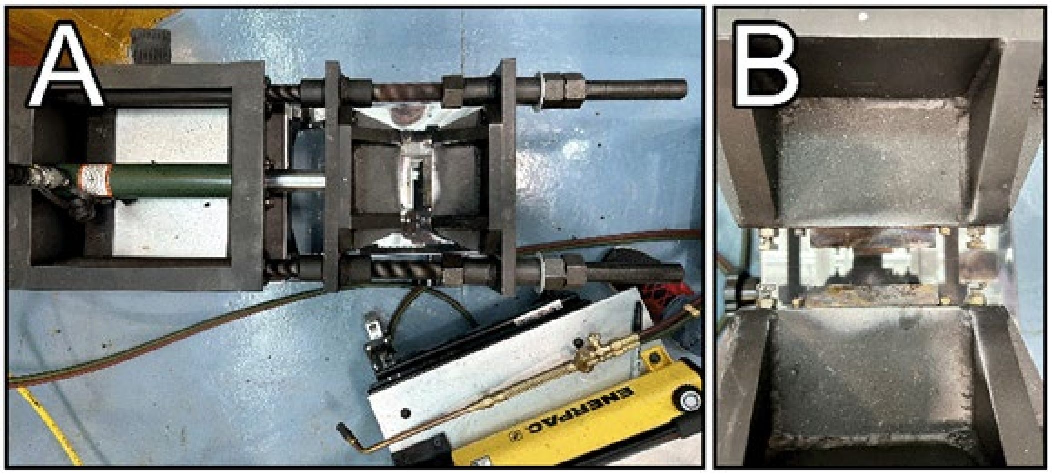

Fig. 4 Stem crimping vise setup (A) and close-up of the crimping jaws (B)

3.3.3 Bakeout Furnace

The bakeout furnace (Fig. 5) is used to evacuate any residual contaminants (moisture, oxygen, organics, etc.) that may be present in a vessel after it is loaded with powder. This system also consists of two components. The first is a commercially available pottery kiln that is capable of sustained temperatures up to 500 °C or greater. The kiln is modified by cutting the top in half and drilling holes in it to allow the vessel stems to protrude out of the top. The split top allows sealed vessels to be loaded and unloaded with ease while allowing minimal heat loss. The second component is a custom-designed and custom-built rolling stand that is easily moved in and out of position with the kiln. The frame is built from 80/20 extruded aluminum framing and supports two Edwards RV8 vacuum pumps and one Julabo F-250 Chiller. A custom-built vacuum manifold constructed from fittings that has six connection ports and three diaphragm valves also is mounted to the frame. The right and left sides of the manifold each have one valve, and another is located in-between the third and fourth connection port to allow for isolation in the event of pump or vessel failure. Vacuum levels are monitored by a digital gauge with a sensor located on each side of the manifold. Additional temperature monitoring is achieved by a digital gauge connected to a repositionable thermocouple.

Fig. 5 Bakeout furnace with manifold for multiple HIP can vessels

3.3.4 Argon (Ar) Atmosphere Glovebox

The Ar atmosphere glovebox (Fig. 6) allows powders to be loaded and sealed into vessels in an atmosphere completely free of oxygen and moisture. The glovebox, supplied by LC Technology Systems Inc, has two separate chambers that are isolated from each other with a round door that allows materials to be exchanged easily from one side to the other. Each chamber is made from stainless steel and is approximately 6 ft in length (side to side) by 4 ft in depth (front to back) and 4.5 ft in height (top to bottom). Each chamber also has a well that is approximately 12 inches deep and 24 inches square that sits below the bottom surface of each chamber. Each well can support more than 350 lb. There are four glove ports equally distanced apart at normal user level on the front window of each chamber, and two glove ports located just above eye level. These upper ports allow convenient access to the top of equipment that is in the wells. On the rear window of each chamber, four glove ports are positioned evenly at normal working height to allow access to the rear of the chambers. Each chamber also has a 6-inch-diameter by 12-inches-long vacuum-controlled access chamber to allow for small sample and tool exchange. The left chamber also has an approximately 16-inch cube vacuum-controlled antechamber that allows for larger powder batches and equipment exchange. The right chamber features a 16- by 12-inch-deep purge chamber that is used to pass packed and sealed vessels in and out of the chamber along with other materials. The entire system is supported by a stainless steel frame, which also houses an Edwards RV12 vacuum pump and a rechargeable copper-based gettering system. The system is equipped with a high-efficiency particulate absorbing vacuum filtration system to remove contaminants from the vessel during welding processes.

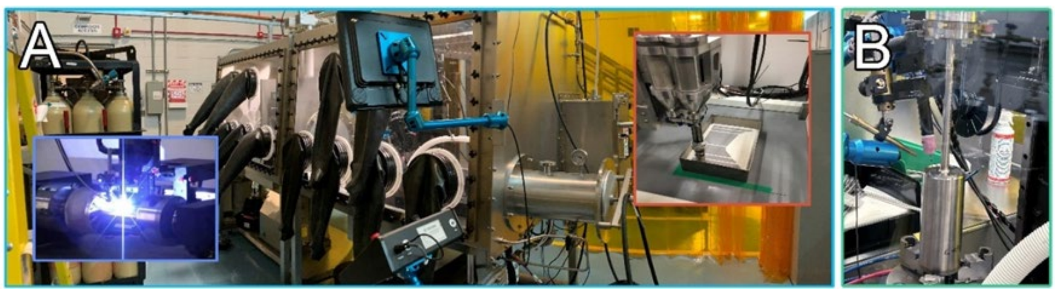

Fig. 6 Glovebox in which the powder is packed (A) and the HIP can vessels are welded (B)

3.3.5 Carver 25T Automated Press

The Carver 25T automated press (Fig. 7) is used to pack powders in vessels in an accurate and repeatable manner. The press is a manually operated, off-the-shelf Carver 3853 Model M hydraulic press with two posts and 9-inch platens. It has an adjustable daylight opening of 0.75 to 16 inches. The press has a Carver AutoPak/25 hydraulic system connected to the press. The hydraulic pump and electronics are located on a shelf underneath the left-hand glovebox chamber while the two-handed actuation controls and control panel have been remotely mounted inside the left-hand chamber. This press sits in the well of the left-hand chamber of the glovebox.

Fig. 7 Carver press inside the glovebox

3.3.6 Weldlogic AWS-210 Automatic Vertical 210A AC/DC Tungsten Inert Gas (TIG) Welder with Wire Feed

Using the TIG, or gas tungsten arc welding process, the AC/DC automatic welder (Fig. 8) fabricates and seals HIP vessels made from virtually any round tubing and stock. The main welding unit is located on a shelf underneath the right-hand glovebox chamber with easy access to on/off controls on the front panel and accessory connections (gas, torch, etc.) on the rear. The control panel is mounted on a cantilevered arm on the front, and a video screen used for positioning and monitoring the weld cycle is located just above it. The accompanying vertical lathe that is used to hold the tubes and vessels sits inside the chamber down in the well. The wire feed module is also located inside the right-hand chamber toward the rear and to the left. All utilities and controls are mounted in sealed vacuum fittings and mounted to pass-throughs in the chamber. A control pendant that allows for rotational positioning of the lathe chuck and vertical positioning of the torch holder arm is also located inside the chamber. All other movements and weld-cycle programming are initiated from the control panel outside the chamber.

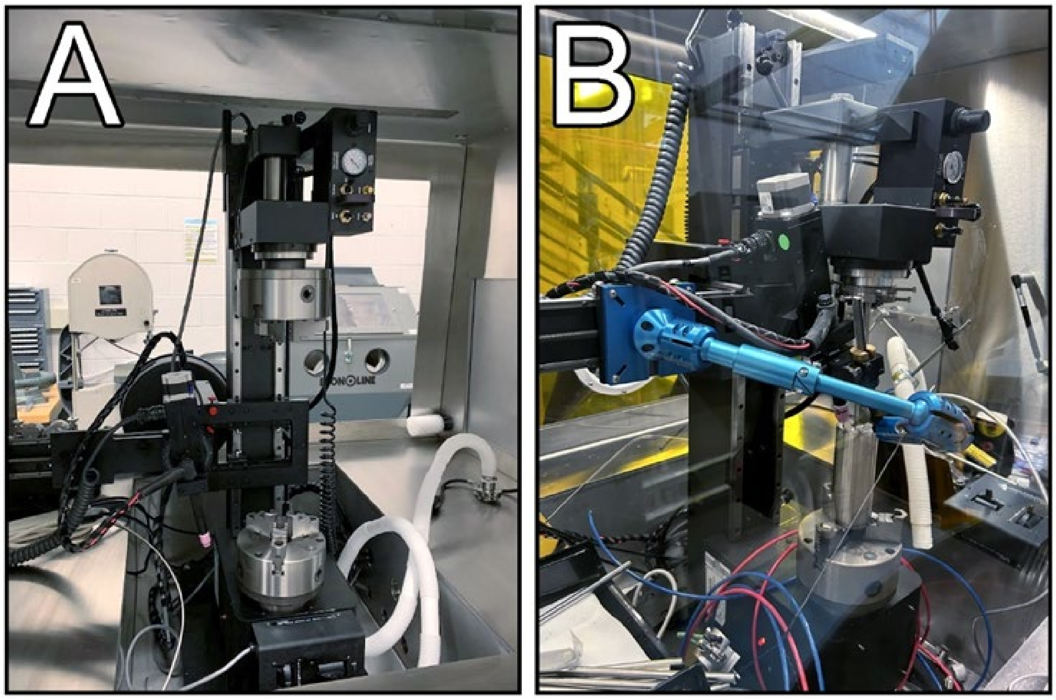

Fig. 8 Automatic vertical welder before installation (A) and after (B), sealed inside the Ar gas glovebox

3.4 Associated Tooling/Fixturing

The following are pieces of equipment and tools that are used to supplement the loading and sealing of HIP vessels.

3.4.1 Powder Loading Tools (Manual Loading Only)

A vessel support base is a round base made from Delrin, aluminum, or steel. It is usually 3–4 times the diameter of the vessel being loaded with powder and approximately 1.5–2.0 inches thick. A groove is cut into the base to allow the weld of the vessel to be centered diametrically, while a protrusion (smaller than the size of the weld) supports the surface of the bottom cap. This helps to transmit the pressing force generated while loading powders to the bottom of the cap instead of the weld. The support base also has a round feature on the bottom that aligns it with the platen on the press and keeps it centered. This is critical for safe operation.

Punches are used to compact powders in vessels and are made from Delrin plastic, aluminum, or stainless steel. Punches should come in varying lengths so they do not extend too far out of the vessel as it is being loaded and cause an unsafe pressing condition. Typically, three to four lengths are sufficient for safe operations. Material selection should be made from calculating the desired pressing force to be applied and comparing that with punch material properties. Punch diameter should generally be about 0.010 inches smaller than the diameter of the can—tighter diameters when using powders that adhere to the sidewalls of the vessel when packing can stick and become difficult or impossible to remove. Looser punch fits can allow too much powder to "blow by" during pressing and not fully compact around the edges. Larger punches should also have a chamfered alignment feature on top that guides into the hole on the top platen of the press as force is being applied; this ensures perfect alignment and an even powder compaction.

Stem cap gauges are made from a stem cap with the top cap turned down to allow easier insertion into a loaded can. The gauge is used to determine if more powder needs to be added or if some powder needs to be removed so the top chamfer of the vessel is in perfect alignment with the chamfer on the stem cap when inserted into a loaded vessel.

3.4.2 Welding and Sealing Tools/Equipment

A depth rod is used to determine the top of the "bullet" after it has been inserted into the stem of a loaded and sealed vessel. The rod can be made from any solid or tubular materials that may be inserted easily into the stem and can be marked with a marker.

Ball valves with compression fittings are used to isolate loaded vessels from the atmosphere when they are moved from the glovebox to the bakeout furnace. These valves must be applied after the bullet has been dropped down the stem, otherwise the bullet will not be able to be properly positioned.

Stem cooling jackets clamp around the stems of loaded vessels to protect the seals of the ball valves from thermal distortion outside the furnace's heating zone when baking out at higher temperatures by allowing cooled water from the chiller to circulate around them.

3.5 HIP Canning Process

The manual loading process is as follows:

1) To determine vessel powder capacity, first the volume of the vessel must be calculated.
2) Determine the amount of powder required to fill the vessel—theoretical density of the powder is normally used to estimate how much is needed. A target of approximately 60% of full density is used when loading the vessels.

3) Determine the amount of powder to use for each layer. Through repeated experimentation, it has been determined that 11–15 layers of the same powder mass produce repeatable consolidations after HIP. This is used only as a guideline; initial procedures were developed using 1-inch-outer-diameter cans and an internal height of 5 inches. Many factors can affect how much powder can be loaded into a can such as the tap density, particle morphology and size, particle hardness, and so on. Sometimes finer powders and larger can sizes seem to pack better when more layers are used. The key to loading is to achieve the targeted theoretical density of approximately 60% without deforming the vessel.

4) Load the established amount of powder for one layer into the vessel. Lightly tap it to roughly level the layer and then insert the appropriate length punch into the vessel. Insert the punch slowly to minimize the amount of powder that "blows by" the punch. For this reason, finer powder requires more care when inserting punches into vessels.

5) Insert the loaded vessel with the punch into the vessel support base and ensure that the base is properly centered on the platen.

6) Apply the calculated amount of force by activating the press cycle, then remove the punch from the vessel after the pressure has been released.

7) Repeat steps 4–6 until powder level in the vessel is within approximately 0.75 inch from the top. Use the stem cap gauge to estimate how much powder needs to be added to ensure proper positioning of the stem cap. As the powder gets closer to the targeted level, weigh out and add smaller amounts so powder does not need to be removed from the vessel. It is easier to add additional smaller layers than to remove powder, depending on how well the powder compacts and holds together. Softer powder particles generally deform more easily and hold together and can prove more difficult to break apart and remove, while finer and harder powder particles do not compact as easily and are less cumbersome to extract excess from vessels.

8) Weigh the loaded vessel and subtract the weight of the empty vessel to determine the exact amount of powder that has been loaded. Compare this to the calculated value to determine if the loaded vessel meets the desired theoretical density.

The welding and sealing process is as follows:

1) Load the correct weld-cycle program from the external controller and download to the main welding power unit.

2) Position the torch to the appropriate angle and verify the electrode is clean, sharp, and extends the correct amount from the end of the torch.

3) Place the proper filter on top of the powder inside the loaded vessel.

4) Remove any powder residue from the inside of the loaded vessel using a lint-free wipe while taking care not to disturb the powder load.

5) Carefully insert a previously prepared stem cap into the vessel and load into the chuck on the lathe.

6) Position the torch electrode in an appropriate position near the apex of the chamfered edges of the vessel and the stem cap on the outside diameter. Use the camera and observe the monitor to get a close-up view of the positioning.

7) Use the "Jog Forward/Jog Reverse" functions on the external controller while watching the monitor and rotate the vessel. Observe the gap between the electrode and the vessel to see how centered the vessel is in the chuck. Lightly tap in the appropriate area to center the vessel if required. Smaller vessels normally require more adjustment than larger ones. Once the vessel has been centered and the gap between the torch electrode and the weld joint is consistent, use the "Return to Home" function to get it into the correct starting position for welding.

8) Set the starting electrode gap that has been set in the cycle recipe and press the green start button for the cycle. The weld cycle may be observed on the screen or, with a suitable welding helmet or glasses, through the window of the glovebox chamber.

9) When the weld cycle has completed, check the weld for any gaps or pinholes on the weld. Many times, small gaps and pinholes can be corrected by repositioning the electrode and running the weld cycle an additional time. Larger gaps may have to be corrected manually and, at times, filler may have to be added. It should be noted that the heat-affected zone of the weld increases the more times a cycle is run and can affect the powder in that localized area.

10) Insert a "bullet" into the tube and check its location by sliding the depth rod into the tube until it contacts the top of the bullet. Place a mark at the top of the stem tube on the depth rod and extract the depth rod. Place the depth rod directly beside the stem and place a mark on the side of the stem at the bottom of the rod to annotate where the top of the bullet is inside the stem. It is important to place the bullet inside the stem tube before the next step,

otherwise it will not be possible to insert the bullet into the stem without shortening the stem. Not inserting a bullet can (and probably will) result in a failed weld and ruin the sample during the HIP cycle.

11) Place a valve on top of the stem tube and tighten the compression fitting. Ensure the valve is closed before moving out of the glovebox through the purge chamber.

The bakeout process is as follows:

1) Using the stem crimper, partially crimp the stem above the black mark that was placed to locate the top of the bullet. Ensure the valve stays tightly closed during this step. Do not fully crimp the stem, especially when it is cold; the partial crimp is only meant to keep the bullet from being drawn out of the stem when vacuum is applied.

2) Connect one of the vacuum ports on the bakeout stand to the valve of the vessels and tighten.

3) Attach the water jacket clamp to the stem just below the valve and turn on the flow valves for each position that will be active during the bakeout cycle.

4) Turn on the vacuum pump with the first isolation valve closed and the valves to each vessel in the closed position. Note the vacuum level after a few minutes of running.

5) After the vacuum level has stabilized and a realistic level is achieved, open the isolation valve and observe the vacuum level. The level should initially rise, and then after a few minutes return to the stabilized level when the valve was closed. Some leakage may be normal for your system—just ensure that it is not excessive.

6) Very slowly open the ball valve on the stem of the vessel. Opening the valve too fast can result in powder being pulled out of the can; avoid this condition as much as possible. Again, observe the vacuum level, it should rise and then after a few minutes return to the baseline that was established when all the valves were closed. Large variations are indicative of a vacuum leak in the vessel. Multiple vessels connected to the system can be checked independently by opening and closing the stem valves one at a time. When a leak is detected, a small pinhole on the stem tube to the top cap interface is often the culprit. This is easily remedied by a small tack weld completed with a manual TIG welder.

7) After determining that all the vessels are completely airtight, allow the pump to run at least for several hours and ensure that the vacuum level is stabilized. Small 1-inch-diameter cans usually equilibrate quickly and do not require much time. Large cans can take overnight or a full day to reach a steady state. Ensure stability before applying any heat from the kiln.

8) Note the vacuum level and begin heating the kiln to 125 °C for 30 h. As the temperature rises, the vacuum level will slowly increase; after a time at the set temperature, the vacuum level will return to the baseline value. This indicates that any contamination or moisture that can volatilize at that temperature has been extracted.

9) Above the temperature of 125 °C in the previous step, the chiller must be started to prevent thermal deformation of the ball valve seals.

10) After vacuum level stabilization, start the next heating cycle of the kiln to 250 °C for 30 h. Again, note the rise and fall of the vacuum level after temperature stabilization. Once equilibrium has been reached, it is acceptable to move onto the next heating cycle; all 30 h do not have to be used if it is evident that all contaminants have been evacuated from the vessels.

11) Complete the heating and stabilization cycles of the vessels in the kiln for 350 and 450 °C. At this time, higher temperatures have not been deemed necessary and have not been attempted. Unconventional materials and conditions may require adjustments to this schedule. For nanocrystalline metals/alloys, any bakeout temperature/cycle employed should be balanced against the inherent grain growth temperature and/or kinetic of the powder.

12) Allow the vessels to cool completely and allow the chiller and vacuum pump to run with the stem ball valves open until ready to crimp. Crimping must be done immediately after removal from the bakeout apparatus.

The stem crimping and sealing process is as follows:

1) Preheat the vessel stem with the oxygen-acetylene torch to a dull-red glow, taking care not to overheat the stem and melt a hole through it.

2) Using the stem crimping vise, partially crimp the vessel stem four to five times approximately 12 mm apart. Do not fully crimp the stem with these crimps.

3) Heat the vessel stem further until it is a bright orange to yellow. The intention is to raise the temperature of the stem to the point where it will

fuse together in the next step. Extreme care must be taken to ensure that the stem is not melted through.

4) Place at least three full crimps, one between each of the partial crimps on the vessel stem.
5) Cut off the vessel stem about 10 mm above the last (top) full crimp.
6) Using the hand TIG welder, immediately weld the top of the vessel stem closed. Ensure no pinholes are present in the weld.

4. Conclusions

The development and implementation of these pieces of equipment and processes has led to the following conclusions:

- The systematic methodology outlined for the preparation and assembly of HIP cans demonstrates optimized fabrication procedures, ensuring the integrity and quality of the final product.
- Through meticulous steps such as precise powder preparation and sealing techniques, the fabrication process contributes to enhanced material consolidation, crucial for achieving desired material properties and performance.
- The controlled heating and vacuum conditions employed during the bakeout process effectively removes contaminants and moisture, ensuring the purity of the encapsulated materials and minimizing potential defects in the final product. As a test case, pre- and post-bakeout analyses of powders should be completed by Luvak to confirm a reduction in contaminants has occurred.
- The precision and attention to detail in welding and sealing procedures guarantee hermetic sealing of the vessels, providing assurance against leakage and maintaining the integrity of the encapsulated materials during subsequent processing steps.

List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
AC	alternating current
Ar	argon
ARL	Army Research Laboratory
DC	direct current
DEVCOM	US Army Combat Capabilities Development Command
HIP	hot isostatic pressing
PM	powder metallurgical
TIG	tungsten inert gas

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