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OPERATOR BURDEN IN METAL ADDITIVE MANUFACTURING

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Abstract

Additive manufacturing (AM) is an emerging manufacturing process that creates usable machine parts via layer-by-layer joining of a stock material. With this layer-wise approach, high-performance geometries can be created which are impossible with traditional manufacturing methods. Metal AM technology has the potential to significantly reduce the manufacturing burden of developing custom hardware; however, a major consideration in choosing a metal AM system is the required amount of operator involvement (i.e., operator burden) in the manufacturing process. The operator burden not only determines the amount of operator training and specialization required but also the usability of the system in a facility. As operators of several metal AM processes, the Manufacturing Demonstration Facility (MDF) at Oak Ridge National Labs is uniquely poised to provide insight into requirements for operator involvement in each of the three major metal AM processes. The paper covers an overview of each of the three metal AM technologies, focusing on the burden on the operator to complete the build cycle, process the part for final use, and reset the AM equipment for future builds.

Introduction

Additive manufacturing (AM) of metals can be accomplished by a variety of techniques, including ultrasonic consolidation of metal sheets, directed energy deposition of metal powders blown into a weld pool, or laser melting, binder jetting, electron beam melting of a powder bed, and others [1]–[3]. In selecting a particular technology, an important factor to consider is the resources needed to operate the equipment. Currently, the most widely used metal AM processes are laser melting (LM), binder jetting (aka Indirect 3D Printing), and electron beam melting (EBM). It is commonly believed that the binder jetting process is the most complex of these three technologies due to the sintering and infiltration step; however, this study demonstrates that LM and EBM have their own unique cycle requirements that make them on par with binder jetting in terms of complexity of operation. The machines operated at ORNL representing these technologies are an Arcam Q-series electron beam machine, a Renishaw AM250 laser system, and an ExOne MFlex binder jetting system. This paper will describe and review these systems with respect to machine build cycle and operator involvement.

The basic operator roles in manufacturing artifacts via powder bed AM are file preparation, build initiation and monitoring, post processing, and machine resetting. First, the file must be prepared such that the geometry is oriented properly and the needed support structure is added to the part. For powder bed fusion processes (EBM and LM), the part must often be physically anchored to the start plate to avoid displacement of the part during spreading. For binder jetting systems, runners that bridge the part to the infiltrate pool must be designed and printed along with the part. After the file is prepared for printing, the machine must be initiated. For EBM and LS, the build chamber must be inerted or evacuated. For all powder bed systems, the powder beds must be heated before the printing begins. Once printer initiation is completed, the print is started and proceeds without the need for operator interaction. From this point, the role of the operator is to simply monitor the build for situations that would damage the machine, such as layer curling or parts shifting in the build.

After the builds are completed, the printed artifacts must undergo post-processing. Post processing for EBM and LS require the print to be manually removed from the start plate along with the pin-like support structures, which are broken off individually with a hand tool. For binder jetting, post processing includes de-powdering the green part and preparing it for sintering and infiltration. Laser-melted parts must be heat-treated to relieve residual stresses induced by the thermal gradients created in the printing process.

Finally, to complete the print cycle, the machines must be cleaned and reset in preparation for the next build job. Resetting the machines is the most significant portion of the operator's role in the manufacturing process. In general, the machines must be cleaned, the powder must be sieved and replaced into the feed bins, and certain machine parts such as filters and shielding must be replaced. A diagram of the basic process flow for metal AM powder bed technologies is provided in Figure 1.

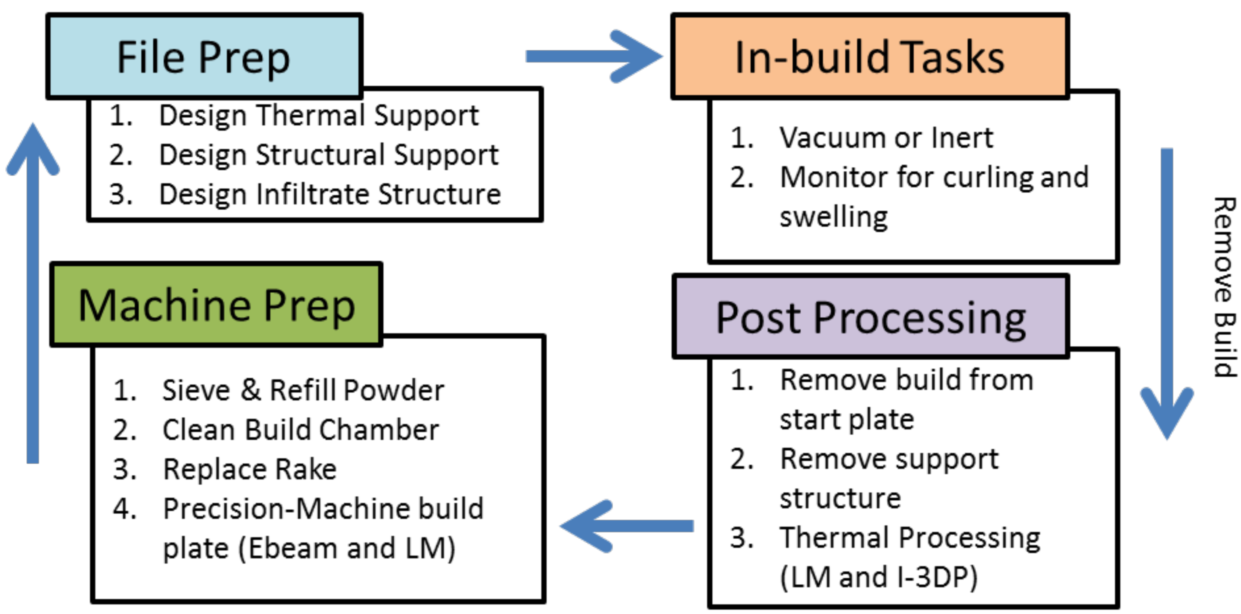

Figure 1: Basic metal powder bed AM process flow

The following sections will briefly describe each of the 3 metal AM process in more depth and cover the operator roles in each process step. It should be understood that this review is an overview of the processes and is therefore simplified. Operating any AM system is a complex task, however, specific details and nuances in each process are left out of this review. Furthermore, each process description does not account for calibration or changing material types (it take hours if not days to properly clean and prep any metal AM machine for new material).

Laser Melting (LM)

Machines made for LM are comprised of above-build powder hoppers and dispensers, a laser apparatus with lenses that divide the laser from the build volume, a wiper blade for smooth the layer, vacuum and gas handling system for evacuating the build volume, and various channels and containers for handling overflow powder and powder refilling. To improve surface finish, the powders used in the LM systems are finer than those of the EBM and binder jetting systems, which also means that powder handling is more difficult in terms of operator safety. This and other aspects of operation contribute to the complexity of operating LM systems.

Process Cycle

The process of creating a part via LM consists of file preparation, build initiation and monitoring, part removal and post processing, and resetting of the machine. The cycle is depicted in Figure 2 below, and each process step is described in detail in this section.

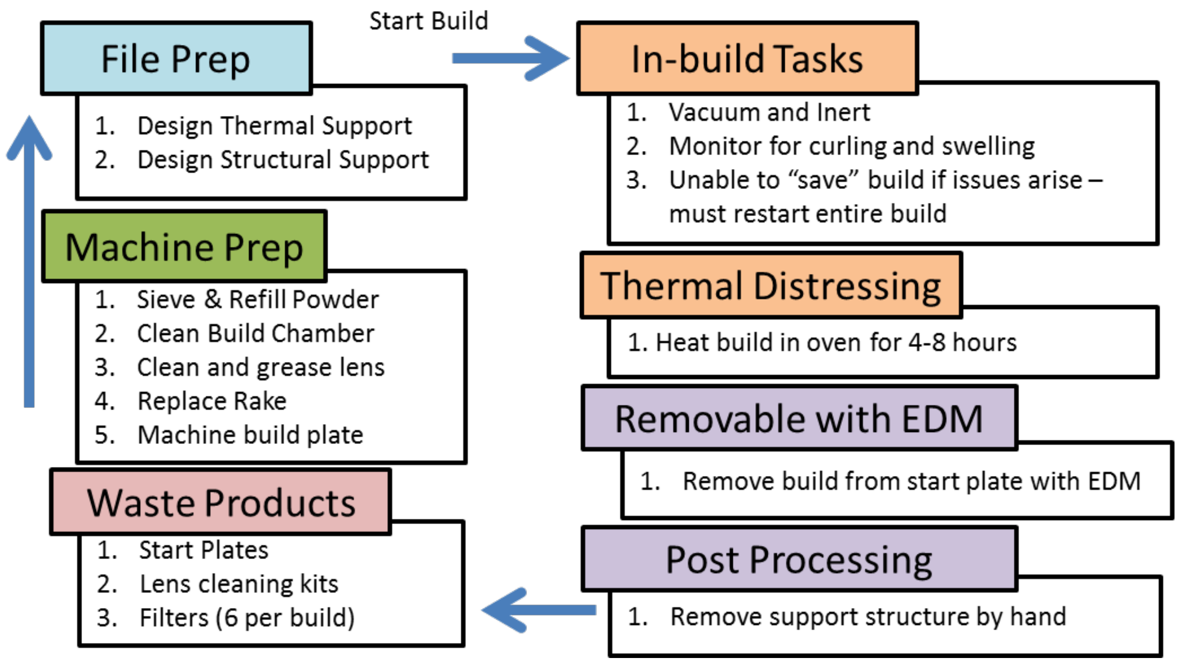

Figure 2: Process cycle for LM

File Preparation

Unlike EBM, SLM machines do not perform a partial sinter of the powder around the part, so the part is surrounded by loose, lower-temperature powder. As a result, all printed parts must be attached to a start plate via specially designed support pins that prevent the build from warping due to thermal stresses. This type of support is called "thermal support." Another type of support is needed called “mechanical support” which prevents the part from shifting in the build due to the spreading of power with each layer with the wiper blade. The mechanical and thermal support are added to the build objects via Magics© software and require some knowledge and experience to design properly. Also, build orientation is critical with LM as over-hanging features can become charred or distorted, so special care is needed by the operator to angle or modify the part to avoid this issue. Overall file preparation can take a several hours to several days depending on the complexity of the build.

Build Initiation and Monitoring

Once the file is modified for printing, the initiation of the print begins with the vacuuming and inerting of the build chamber, which takes approximately 30 minutes to complete. After evacuation and inerting, the build proceeds automatically and only requires that the operator monitor for part warping, which can damage the wiper blade and create defects in the print. If this occurs, the operator may allow the build to continue if the damage is minimal or stop and reset the build completely. For longer builds, the operator may be required to recover and refill powder hoppers during the build.

Build recovery and post processing

Once the build is completed, the chamber is vented and the part is raised above the build service. As the part is raised, the operator must sweep the powder surrounding the build into the overflow bins within the build chamber. From here, the part and the attached start plate are removed from the machine. At this point, the part and the start plate together may undergo thermal post-processing to relieve residual stresses if the geometry is medium or large in size. This consists of heating the part and start plate to 400-800 degrees Celsius for 1-4 hours, depending on the material and mass. After treatment, the support material that connects the printed part with the start plate must be cut via wire electrical discharge machining (EDM) and the remaining structure is removed by the operator via pliers. Thus, the LM process has at least 2 extra post-processing steps and requires access to a high-temperature oven as well as an EDM or other cutting machine for operation.

Machine Resetting

The tasks to complete to prepare the machine for the next build include the following:

1. Powder sieving
2. Cleaning of the build chamber (vacuum and wipe with alcohol)
3. Replacement of argon gas (every 100 hours, ~ every other build)
4. Cleaning the lens and lubricate the o-ring
5. Changing 6 different filters
6. Install new build plate
7. Refilling the powder bins

An experienced operator can complete these tasks in 2-3 hours, (excluded start plate preparation) however an additional technician is needed for the filter changing. The 6 filters to be changed contain fine particles which are hazardous, but these filters must be changed out every build. The filters are encapsulated and can be removed from the machine without exposing the fine particles to the surrounding environment. To remove the filters from the encapsulation, however, water must be poured into the capsule immediately upon opening, soaking the filter and the particles. The soaking by water eliminates the possibility of the fine particles becoming airborne. From here, the filters are removed from the capsule and disposed of as hazardous waste. Due to the mechanics of filter replacement, two technicians are required to perform this task safely.

Due to the sensitivity of the laser, the start plate must be precision machined parallel and flat to a tolerance of 0.003" and a mill-finish roughness. Also, the lens that separates the laser system from the powder-filled build chamber must be removed, cleaned with a lens cleaning kit until no streaks are visible. Finally, the o-ring that seals the lens must be greased, and the lens must be mounted.

Electron Beam Melting

Electron beam melting is a powder bed fusion process comprised of primarily a powder bed system, an electron beam, and a vacuum chamber. The electron beam is created by inducing a charge between a cathode and anode, the cathode being a specialized filament and the anode is the start plate. The electrons are directed via electromagnetic fields to a precise location in the top of the build volume, and the electrons collide with the powder particles inducing a melt pool. A vacuum is maintained within the build chamber during operation since gas molecules would interfere with the trajectory of the electrons from the EBM, and the build chamber maintains a temperature of 500-1100 degrees Celsius depending on the material.

Process Cycle

The process cycle for electron beam melting is depicted in Figure 3 below, and the individual steps are described in detail in this section.

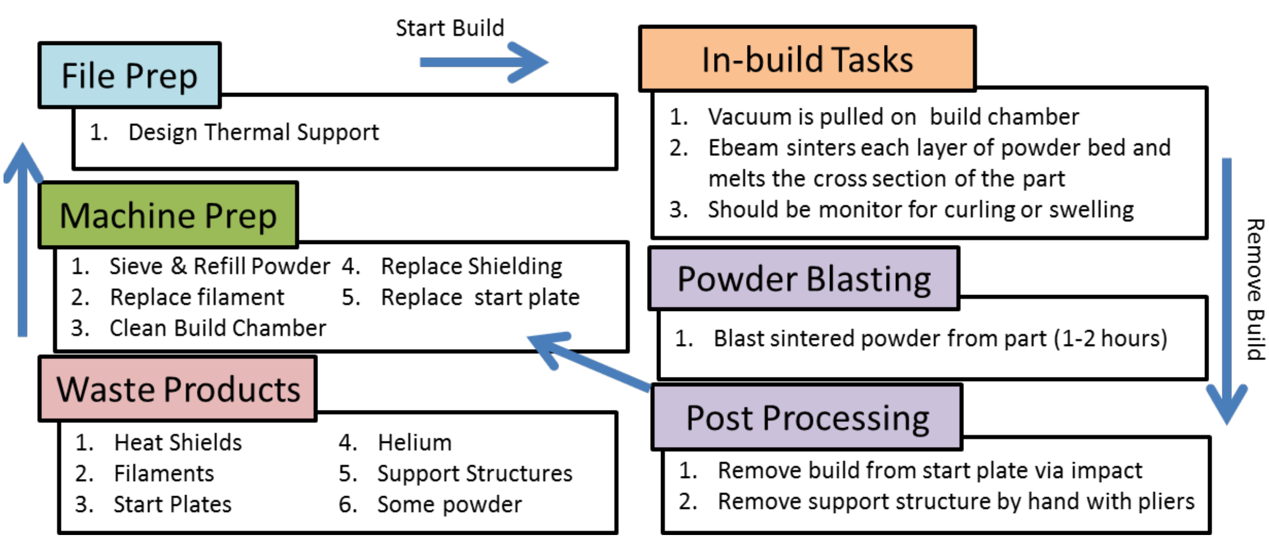

Figure 3: Process cycle for operating EBM system

File Preparation

Parts printed via EBM must be physically anchored to a start plate to prevent movement of the part within the powder bed during powder spreading with the wiper blade. Because the powder surrounding the part is partially sintered during printing, thermal distortion is not an issue with EBM as it is with LM, and supports are not needed to combat thermal warping. An operator will use software specialized for support structure design to add these structures to the build geometry. The file is then converted to a printable format and sent to the printer.

Build Initiation and Monitoring

The first step of the printing process is to preheat and draw a vacuum in the build chamber, after which the build can proceed. The spreading tool utilized in the Arcam system is a comb-like metal rake. The individual combs on the spreader are robust and flex individually when they collide with raised portions of build. Thus, damage to the spreader and the subsequent imperfections in the build are not an issue with the Arcam system as with the Renishaw system, and monitoring for this is not necessary. However, periodic monitoring for defects in the build is needed.

Build recovery and post processing

Upon completion a part in the EBM process, the entire build volume is removed from the machine. Since the powder surrounding the printed part is partially sintered, the build volume comes out in a sintered block. The block is then put into a blasting station where recycled build powder is blasted onto the part, removing the sintered portions. From here, the part can be removed from the start plate via impact with a hammer. Finally, the support structures can be manually plucked or chiseled away from the part via hand tools. Between EBM, SLM, and I-3DP, objects produced by EBM technology typically require the least amount of post-processing due to the ease with which the start plate can be removed and the lack of residual stresses induced in the part during manufacturing. A disadvantage of EBM, however, is that if the blasting gun cannot reach the inside of a narrow channel, the sintered powder within the channel does not get removed or requires significant effort to remove. Therefore, depending on the complexity of the geometry, depowering can be either simple or complex.

Machine Resetting

Resetting the Arcam system requires the following steps to be completed:

1. Build chamber cleaned with vacuum
2. Heat shields removed and replaced if needed
3. Filament removed and replaced if needed
4. Used powder sieved
5. Powder restocked
6. Start plate replaced and treated

An experienced technician can complete these tasks within 2 hours. The most difficult step in the resetting process is the treating of the start plate, which can include stress relief via thermal processing and surface treatment that is performed by the EBM. Since the volume of gas used in the process is very low, the helium tank requires changing every 10 builds or so. Thus, the majority of the resetting process time is comprised of cleaning the machine, sieving the used powder, and replacing the filament, heat shield, start plate, and powder.

Binder Jetting

Binder Jetting utilizes inkjet technology to selectively deposit a liquid binder into a powder bed. After the part is shaped with binder, the entire powder bed is then moved to a curing oven where the bed is heated to around 200 degrees Celsius. Once the binder is fully cured, the part is removed from the build bed, depowdered, and prepared for sintering and infiltration. Sintering is done in a high temperature oven, and due to the low density of the sintered part, current binder jet parts are infiltrated with a secondary material. A common material combination utilized by the ExOne Corporation is printed Stainless Steel 316 with a bronze infiltrate. The result is a near-full density part with a ratio of printed metal to infiltrate of around 60/40 [4].

Process Cycle

In addition to the printing, binder jetting consists of binder curing and a sintering and infiltration steps. Thus, the process cycle consists of file preparation, shaping of the part via binder printing, curing of the binder in a low-temp oven, sintering and infiltration of the cured, green part, post processing of the part, and finally, preparing the machine for the next build job. The process cycle is illustrated in Figure 4.

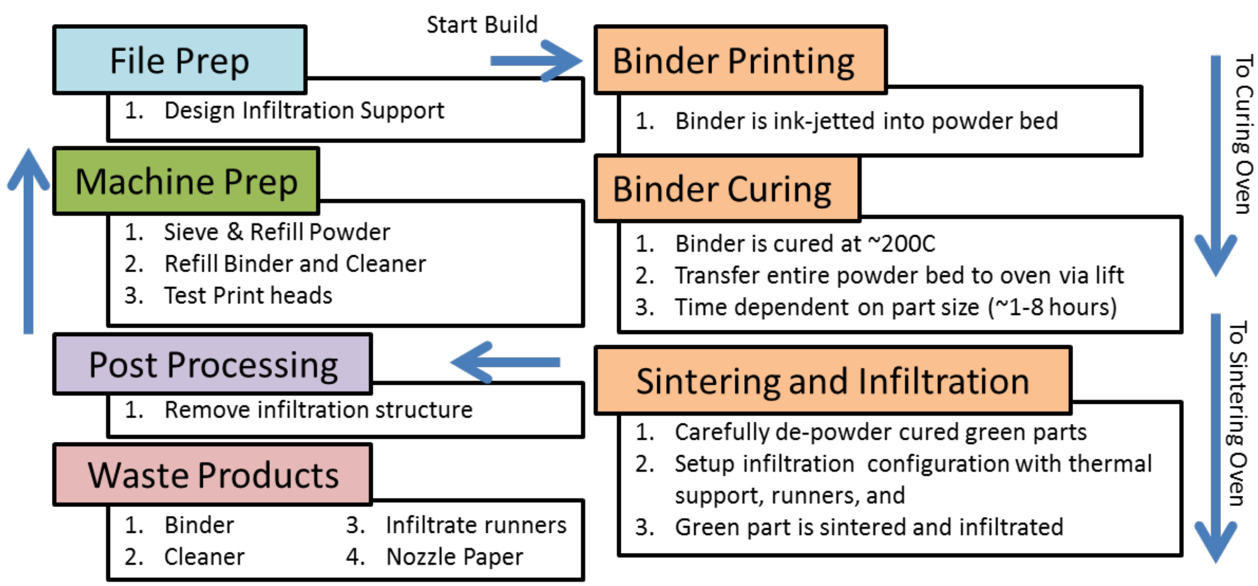

Figure 4: Process cycle for binder jetting

File Preparation

Since the shaping process in binder jetting is performed without a concentrated heat source, the powder bed that surrounds the printed part is sufficient to support the part during the build. In other words, since there is no thermal warpage or curling during the I-3DP printing process itself, there is no need to design a support structure around the part. Finally, every build requires a structure to connect the printed part with infiltration pool, so a sacrificial connecting feature must be digitally added to the part, and runners must also be printed.

Build Initiation and Monitoring

The binder jet process consists of spreading layers of powder and inkjetting binder into the powder to form the appropriate 2D profile of the part layer. Depending on the geometry and volume of build, the spreading and curing times of certain layer ranges may be sped up or slowed down to decrease build time or prevent smearing of the layers, respectively. To initiate a build in a binder jet system, the powder bed must be prepared by spreading and heating a few foundational layers until the appropriate bed temperatures is reached. During the 3D printing process itself, no thermal warpage or significant machine setting fluctuations occur, so build monitoring the build during this phase is just to identify smearing between the roller and the printed layer. If smearing occurs, the operator typically just slows the heating and spreading settings down as smeared features can be manually corrected in the green part after the print is cured and depowered. For lengthy builds, overflow powder can be reclaimed and refilled into the feed hopper without the need to pause the build. However, if the powder supply in the hopper is depleted mid-build, the machine pauses the build until the operator restocks the powder and resumes the print.

Build recovery and post processing

Once the binder jetting phase is completed, the entire powder bed must be transferred to a curing oven and baked until the binder is cured. The curing process takes from 2-8 hours depending on the printed volume. After curing the binder, the “green” part must be carefully removed from the powder bed. This is generally done a de-powdering station where the build box can be gradually lowered and the powder brushed away from the top of the part to the bottom. Once the part is de-powdered, the part is added to the sintering crucible along with the infiltrate, thermal support and infiltrates runners. The part, runners, and infiltrate material is placed first in the crucible and then buried in the thermal support gravel. This general configuration is depicted in Figure 5.

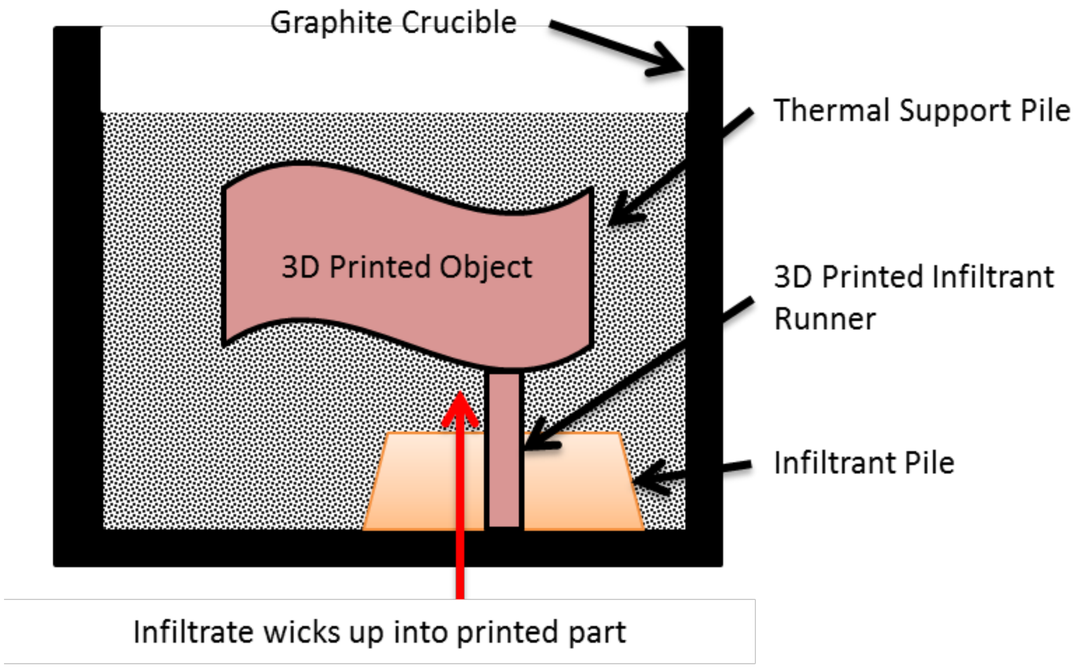

Figure 5: Setup configuration for the sintering and infiltration of I-3D printed green parts

The final step in the binder jetting process is the removal of the infiltrate runner(s), which is typically done with a rotary cutting hand tool. The parts can then be media blasted or milled with polishing media to improve surface finish.

Machine Resetting

To reset a binder jet machine for the next build, the support powder from the previous build must be sieved and replaced. Also, the print heads must be checked by doing a test print pattern and identifying missing jets. Finally, the gas to the sintering furnace must be replaced if needed. An experienced operator can reset the machine in 1 hour.

<u>Operation Complexity and Training Comparison</u>

Although the binder jetting process requires additional process steps to complete, the complexity of operating a binder jet machine much less than its LM and EBM counterparts. To illustrate this point, the amount of training required to operate these systems can be compared. For basic operability Rennishaw system, 2 weeks of training is scheduled with hands-on time at about 30 hours. For Arcam, 2 weeks of training is scheduled with approximately 40 hours hands-on time. For the ExOne system, 3 days of training are required with most of that being hands-on time. Thus, it can be surmised that binder jetting is perhaps a less complex process than EBM or LM in terms of operation.

Conclusions

A critical aspect of selecting a metal AM system is an understanding the requirements for operating that system. It is widely believed that the binder jetting is the more complex of all the metal powder bed AM systems, however LM and EBM systems have their own unique extra processing steps to consider. For laser and electron beam systems, it's important to understand the extent to which builds must be prepped with support structures and the burden of removing those structures in post processing. Also, laser prints must be thermally treated and electron beam prints must be powder blasted. This paper provides an overview of each technology's process cycle and the operator tasks with each cycle.

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