# 8 Binder Jetting

**Abstract**
Binder jetting methods were developed in the early 1990s, primarily at MIT. They developed what they called the 3D Printing (3DP) process in which a binder is printed onto a powder bed to form part cross sections. This concept can be contrasted with powder bed fusion (PBF), where a laser melts powder particles to define a part cross section. A wide range of polymer composite, metals, and ceramic materials have been demonstrated, but only a subset of these are commercially available. Some binder jetting machines contain nozzles that print color, not binder, enabling the fabrication of parts with many colors. Several companies licensed the 3DP technology from MIT and became successful machine developers, including ExOne and ZCorp (purchased by 3D Systems in 2011). A novel continuous printing technology was been developed recently by Voxeljet that can, in principle, fabricate parts of unlimited length.

## 8.1 Introduction

The original name for binder jetting was Three-Dimensional Printing (3DP) and it was invented at MIT and has been licensed to more than five companies for commercialization. In contrast to the printing processes described in Chap. 7, binder jetting (BJ) processes print a binder into a powder bed to fabricate a part. Hence, in BJ, only a small portion of the part material is delivered through the print head. Most of the part material is comprised of powder in the powder bed. Typically, binder droplets (80 μm in diameter) form spherical agglomerates of binder liquid and powder particles as well as provide bonding to the previously printed layer. Once a layer is printed, the powder bed is lowered and a new layer of powder is spread onto it (typically via a counter-rotating rolling mechanism) [1], very similar to the recoating methods used in powder bed fusion processes, as presented in Chap. 5. This process (printing binder into bed; recoating bed with new



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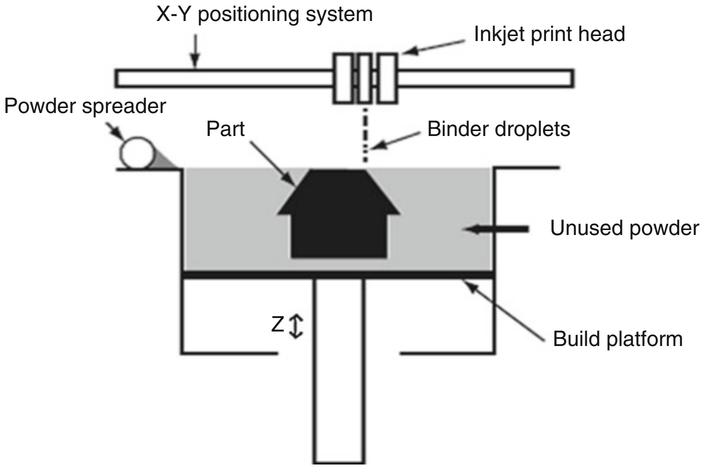


**Fig. 8.1** Schematic of the binder jetting process

layer of powder) is repeated until the part, or array of parts, is completed. A schematic of the BJ process is shown in Fig. 8.1.

Because the printer head contains several ejection nozzles, BJ features several parallel one-dimensional avenues for patterning. Since the process can be economically scaled by simply increasing the number of printer nozzles, the process is considered a scalable, line-wise patterning process. Such embodiments typically have a high deposition speed at a relatively low cost (due to the lack of a high-powered energy source) [1], which is the case for BJ machines.

The printed part is typically left in the powder bed after its completion in order for the binder to fully set and for the green part to gain strength. Post-processing involves removing the part from the powder bed, removing unbound powder via pressurized air, and infiltrating the part with an infiltrant to make it stronger and possibly to impart other mechanical properties.

The BJ process shares many of the same advantages of powder bed processes. Parts are self-supporting in the powder bed so that support structures are not needed. Similar to other processes, parts can be arrayed in one layer and stacked in the powder bed to greatly increase the number of parts that can be built at one time. Finally, assemblies of parts and kinematic joints can be fabricated since loose powder can be removed between the parts.

Applications of BJ processes are highly dependent upon the material being processed. Low-cost BJ machines use a plaster-based powder and a water-based binder to fabricate parts. Polymer powders are also available. Some machines have color print heads and can print visually attractive parts. With this capability, a market has developed for colorful figures from various computer games, as well as personal busts or sculptures, with images taken from cameras. Infiltrants are used to strengthen the parts after they are removed from the powder bed. With either the starch or polymer powders, parts are typically considered visual prototypes or light-duty functional prototypes. In some cases, particularly with elastomeric infiltrants, parts can be used for functional purposes. With polymer powders and wax-based infiltrants, parts can be used as patterns for investment casting, since the powder and wax can burn off easily.

For metal powders, parts can be used as functional prototypes or for production purposes, provided that the parts have been designed specifically for the metal alloys available. Molds and cores for sand casting can be fabricated by some BJ machines that use silica or foundry sand as the powder. This is a sizable application in the automotive and heavy equipment industries.

## 8.2 Materials

### 8.2.1 Commercially Available Materials

When Z Corporation first started in the mid-1990s, their first material was starch based and used a water-based binder similar to a standard house-hold glue. At present, the commercially available powder from 3D Systems is plaster based (calcium sulfate hemihydrate) and the binder is water based [2]. Printed parts are fairly weak, so they are typically infiltrated with another material. 3D Systems provides three infiltrants, the ColorBond infiltrant, which is acrylate-based and is similar to superglue, StrengthMax infiltrant which is a two-part infiltrant, and Salt Water Cure, an eco-friendly and hazard-free infiltrant. Strength, stiffness, and elongation data are given on 3D Systems' web site for parts fabricated with these infiltrants. In general, parts with any of the infiltrants are much stiffer than typical thermoplastics or VP resins, but are less strong, and have very low elongation at break (0.04–0.23 %).

Voxeljet [3], on the other hand, supplies a PMMA (poly-methyl methacrylate) powder and uses a liquid binder that reacts at room temperature. They recommend that parts stay in the powder bed for several hours to ensure that the binder is completely cured. For investment casting pattern fabrication, they offer a wax-based binder for use with PMMA powder that is somewhat larger in particle size than the powder used for parts. They claim excellent pattern burnout for investment casting.

For materials from both companies, unprinted powders are fully recyclable, meaning that they can be reused in subsequent builds. A desirable characteristic of powders is a high packing density so that printed parts have a high volume fraction of powder and are strong enough to survive depowdering and clean up operations. High packing densities can be achieved by tailoring powder particle shape or by including a range of particle sizes so that small particles fill in gaps between larger particles. In practice, both approaches are used whenever possible.

Quite a few other infiltrant materials have been marketed by ZCorp and 3D Systems and many users have experimented with a variety of materials, so alternatives are possible that can produce parts with a wide range of mechanical properties.

ExOne markets machines that use either metal or sand powders for metal parts or sand-casting molds and cores, respectively [4]. In the metals area, they currently market 3,166 stainless steel and bronze, 420 stainless steel (non-annealed), 420 stainless steel (annealed), bronze, and Inconel 625. For the stainless steel materials, bronze is used as an infiltrant so that parts are virtually fully dense. Polymer binders are used for the metals. In order to fabricate a metal part, the "green" part is removed from the AM machine, then is subject to three furnace cycles. In the first cycle, low temperature is used for several hours to burn off the polymer binder. In the second cycle, high temperature is used to lightly sinter the metal particles together so that the part has decent strength. If this cycle is too long, the metal particles more completely melt, causing the part to lose dimensional accuracy and its desired shape. After this cycle, the part is approximately 60 % dense. In the final cycle, a bronze ingot is placed in the furnace in contact with the part so that bronze infiltrates into the part's pores, resulting in parts that are 90–95 % dense.

An exception to the light sintering and infiltration process is the new Inconel 625 material announced by ExOne in 2014. Although they use a binder, the Inconel material can be sintered to virtually full density (ExOne claims greater than 99 % dense) while maintaining acceptable dimensional accuracy. If this process can be extended to other metals, it could change the economics of metal AM significantly.

Both ExOne and Voxeljet market machines that use sand for the fabrication of molds and cores for sand casting. ExOne offers a silica sand and two-part binder, where one part (binder catalyst) is coated on a layer and the second part is printed onto the layer, causing a polymerization reaction to occur and binding sand particles together. They claim that only standard foundry materials are used so that resulting molds and cores enable easy integration into existing manufacturing and foundry processes. Voxeljet also offers a silica sand with an inorganic binder and claims that their materials also integrate well into existing foundry processes.

Finally, ExOne markets a soda-lime glass material for use in fabricating artwork, jewelry, or other decorative objects. Different colors and finishes are available. An organic binder is used that requires an elevated temperature curing cycle. Then, parts need to be fired at high temperature to sinter the glass particles and impart decent strength and stiffness.

### 8.2.2 Ceramic Materials in Research

A wide range of materials has been developed for BJ by researchers. Printing into metal and ceramic powder beds was first demonstrated in the early 1990s. Various powder mixes, including compositions and size distributions, have been explored.

Traditional powder-based BJ of ceramics involves the selective printing of a binder over a bed of ceramic powder [5]. Fabrication of ceramic parts follows a very similar process compared with metal parts. Green parts created by this process are subjected to a thermal decomposition prior to sintering to remove the polymer binder. After binder burn off, the furnace temperature is increased until the ceramic's sintering temperature is reached. Sometimes an infiltrant is used that reacts to form a ceramic binder. Another possibility is to infiltrate with a metal to form a ceramic-metal composite. The first report of using BJ for the fabrication of ceramics was in 1993; fired components were reported as typically greater than 99.2 % dense [5]. Alumina, silica, and titanium dioxide have been made with this process [6].

Research involving the BJ of ceramics encountered early setbacks because of the use of dry powders. The fine powders needed for good powder bed density did not generally flow well enough to spread into defect-free layers [5]. Furthermore, since green part density was inadequate with the use of dry powders, isostatic pressing was implemented after the printing process. This extraneous requirement severely limits the types of part shapes capable of being processed.

To counteract the problems encountered with recoating a dry powder bed, research on ceramic BJ has shifted to the use of a slurry-based working material. In this approach, layers are first deposited by ink-jet printing a layer of slurry over the build area. After the slurry dries, binder is selectively printed to define the part shape. This is repeated for each individual layer, at the cost of significantly increased build time. Multiple jets containing different material composition or concentration could be employed to prepare components with composition and density variation on a fine scale (100 μm) [7]. Alumina and silicon nitride have been processed with this technique, improving green part density to 67 %, and utilizing layer thicknesses as small as 10 μm [8].

Recently, a variation of this method was developed to fabricate metal parts starting with metal-oxide powders [9]. The ceramic BJ is used until the furnace sintering step. While in the furnace, a hydrogen atmosphere is introduced, causing a reduction reaction to occur between the hydrogen and the oxygen atoms in the metal-oxide. The reduction reaction converts the oxide to metal. After reduction, the metal particles are sintered to form a metal part. This process has been demonstrated for several material systems, including iron, steels, and copper. Unfortunately, reaction thermodynamics prevent alumina and titanium oxide from being reduced to aluminum and titanium, respectively.

This Metal-Oxide Reduction 3DP (MO3DP) process was demonstrated using a Z405 machine [10]. Metal-oxide powders containing iron oxide, chromium oxide, and a small amount of molybdenum were prepared by spray drying the powder composition with polyvinyl alcohol (PVA) to form clusters of powder particles coated with PVA. Upon reduction, the material composition formed a maraging steel. Water was selectively printed into the powder bed to define part cross sections, since the water will dissolve PVA, causing the clusters to stick together. A variety of shapes (trusses, channels, thin walls) were fabricated using the process to demonstrate the feasibility of producing cellular materials.

The main advantage of BJ, in the context of manufacturing cellular materials, lies in its economic considerations. Simply put, the BJ process does not require high energy, does not involve lasers or any toxic materials, and is relatively inexpensive and fast. Part creation rate is limited to approximately twice the binder flow rate. A typical inkjet nozzle delivers approximately 1 $cm^3$/min of binder; thus a machine with a 100 nozzle print head could create up to approximately 200 $cm^3$/min of printed component. Because commercial inkjet printers exist with up to 1,600 nozzles, BJ could be fast enough to be used as a production process.

## 8.3 Process Variations

Almost all commercially available BJ machines use the architecture shown in Fig. 8.1. An array of print heads is mounted on an XY translation mechanism. If the process is capable of printing colored parts, some print heads are dedicated to printing binder material, while others are dedicated to printing color. Typically, the print heads used are standard, off-the-shelf print heads that are found in machines for 2D printing of posters, banners, and similar applications. Parts are fabricated in batches, just like every other AM process.

Powder handling and recoating systems are similar to those used in powder bed fusion processes. Differences arise when comparing low-cost visual model printers (for plaster or polymer powders) to the metal or sand printers. For the low-cost printers, powder containers (vats) can be hand-carried. In the latter cases, however, powder beds can weigh hundreds or thousands of pounds, necessitating different material handling and powder bed manipulation methods. For the sand printers, the vats utilize a rail system for conveying powder beds to and from depowdering stations and cranes are used for transporting parts or molds.

The capability of continuous printing or of fabricating parts that are larger than the AM machine fabricating them has been discussed in the research community. In recent years, two different approaches have been demonstrated for continuous printing of parts. One approach is being commercialized by Voxeljet in 2013 and is based on linear translation of the part being fabricated. The second approach is called spiral growth manufacturing and was developed by researchers at the University of Liverpool, UK.

The Voxeljet continuous printing process is a novel idea that utilizes an inclined build plane. That is, the build surface of the powder bed is inclined at an angle of 30°, less than the powder's critical angle of repose. Powder recoating and binder jetting are performed on this inclined build surface. The powder bed translates on a conveyor belt from the front towards the back of the machine. In contrast to typical batch fabrication, parts emerge continuously at the back of the machine. In principle, parts could be infinitely long, certainly much longer than the machine. The continuous part fabrication capability could represent an important step in achieving economical manufacture of moderate to high production volumes of parts.

The second continuous fabrication approach, spiral growth manufacturing (SGM) was invented by Chris Sutcliffe at the University of Liverpool in the early 2000s. The patent US2008109102 is a good reference for further information [11]. In the BJ variant of SGM, the powder bed is circular and rotates continuously. Binder printing and recoating are performed continuously also. As the machine operates, the powder bed indexes downwards continuously to accommodate the

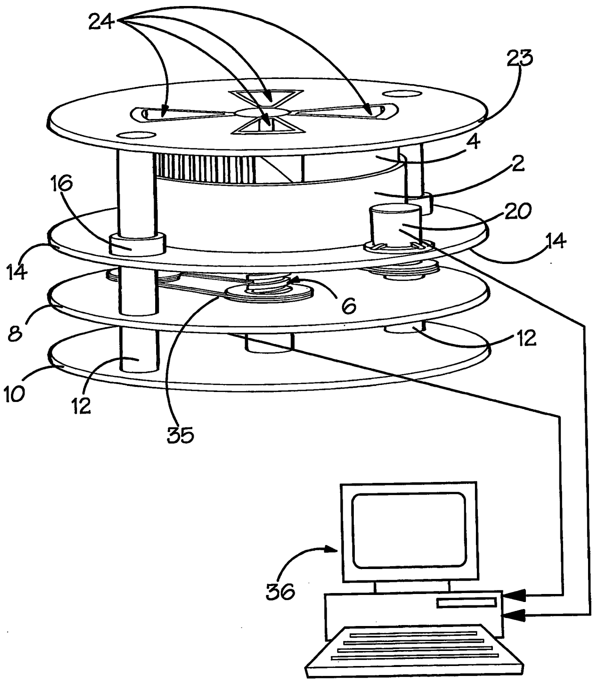


**Fig. 8.2** Schematic of a spiral growth manufacturing BJ machine

next layer of powder. As such, the top layer of powder forms a spiral in the powder bed. A machine schematic from the patent is shown in Fig. 8.2.

In the figure, object 2 is the cylindrical build chamber. Plates 10, 8, 14, and 23 do not rotate; plate 14 supports the build chamber and slides up and down on the pillars 12. The build chamber rotates, driven by the lead screw numbered 6. Four powder supply hoppers are shown by objects 24, so this indicates that the machine has four build stations, each with print heads and recoater mechanism. As a consequence, for each rotation of the build chamber, effectively four layers are deposited and processed. So, for example, if the layer thickness is 0.1 mm, each rotation of the build chamber adds 0.4 mm to the powder bed height and plate 14 and the build chamber must translate downward by 0.4 mm to accommodate this increase in bed height.

Each build station typically contains a print head with multiple nozzles. Since the width of the powder bed is typically greater than the print head width, a linear stage must be used to translate the print head across the powder bed. The linear velocity of the outer edge of the build chamber is greater than the linear velocity at the inner edge, which means that the powder along the outer edge passes the print head at a faster speed. This has important consequences for the printing conditions across the width of the chamber: more binder has to be deposited per unit time along the outer edge compared to the inner edge. Effectively this means that the images being printed have to be pre-skewed in order to compensate for the differences in speed. As an example, Fig. 8.3 shows how an image must be skewed so that the

**Fig. 8.3** Skewing an image for SGM printing

printed image is fabricated properly [12]. This image was printed on a SGM machine with two print heads, hence the two images on the right. Note that the inner edge is on the left side of the image, which is stretched, while the outer edge is compressed.

## 8.4 BJ Machines

A wide variety of powder and binder materials can be used which enables significant flexibility in the process. MIT licensed the BJ technology according to the type of material and application that each licensee was allowed to exploit. ZCorp, Inc. was one company that marketed machines that build concept models in starch and plaster powder using a low viscosity glue as binder. At the other end of the spectrum, ExOne markets machines that build in metal powder, with a strong polymer material that is used as the binder, as well as silica sand for sand casting applications. Voxeljet is a relatively new company that markets BJ machines that use polymer and sand powders for concept models, functional models, investment casting patterns, and sand casting applications.

As of 2012, ZCorp was purchased by 3D Systems and their product line was merged into 3D Systems' ProJet line of printers. These printers are now branded as the ProJet X60 line of printers, with the smallest being the ProJet 160 and the largest being the ProJet 860Pro. Specifications for some of these machines are shown in Table 8.1. Machine names consisting only of numbers fabricate parts that are monochrome only, while suffixes of C, Plus, or Pro indicate that parts can be printed in color, up to the full CMYK color model (Cyan, Magenta, Yellow, Key (black)).

Voxeljet sold their first machine in 2005. They now offer a range of machines from the smallest VX200 to the huge VX4000, which has a 4 m long powder bed. The VX4000 processes foundry sand materials for the sand casting industry. They also market the VXC800, which is the infinitely continuous printer that was

**Table 8.1** Machine specifications for binder printing machines

| Company/ models | Cost (1,000s) | Deposition rate (mm/h) | Build size ($l \times w \times h$) (mm) | Resolution (dpi) | Layer thickness (mm) | Number of nozzles | Materials |
|---|---|---|---|---|---|---|---|
| *3D Systems* | | | | | | | |
| ProJet 160 | $16.50 | 20 | 236 × 185 × 127 | 300 × 450 | 0.1 | 304 | Polymer composite with infiltrants |
| ProJet 260C | $28.70 | 20 | 236 × 185 × 127 | 300 × 450 | 0.1 | 604 | |
| ProJet 860 Pro | $114 | 15 May | 508 × 381 × 229 | 600 × 540 | 0.1 | 1,520 | |
| *ExOne* | | | | | | | |
| Lab Platform | $125 | 6 March | 40 × 60 × 35 | 400 × 400 | 0.05–0.1 | | Stainless steel, bronze, ceramics, glass |
| Flex Platform | $425 | 12 | 400 × 250 × 250 | 400 × 400 | 0.1 | | Above and Inconel |
| Max Platform | >$1,400 | 20 | 1,800 × 1,000 × 700 | 300 × 300 | 0.28–0.5 | | Silica sand, ceramics |
| *Voxeljet* | | | | | | | |
| VX200 | $159 | 12 | 300 × 200 × 150 | 300 × 300 | 0.15 | 256 | PMMA, inorganic sand |
| VXC800 | $700 | 35 | 850 × 500 × 30° | 600 × 600 | 0.15–0.4 | 2,656 | |
| VX4000 | $1,850 | 15.4 | 4,000 × 2,000 × 1,000 | 600 × 600 | 0.12–0.3 | 26,560 | |

**Fig. 8.4** Voxeljet VXC800 machine (Courtesy Voxeljet)

described earlier. A photo of the VXC800 is shown in Fig. 8.4. For this machine, the layer thickness is 150–400 μm and they use 600 dpi print heads. The surface area of the inclined plane is 500 × 850 mm.

The ExOne Corporation markets a line of BJ machines that fabricate metal parts and sand casting molds and cores in foundry sand. Strong polymer binders are required with these heavy powders. As explained earlier, nearly fully dense parts can be fabricated by printing binder into the metal bed, burning off the binder in a furnace at a low temperature, sintering the metal powder during a high temperature furnace cycle, then infiltrating a second metal, such as copper or bronze, at a low temperature. The printed part, when removed from the bed, is a relatively low-density (50–60 %) green part. Other than how the green part is formed, this process is identical to the indirect processing approach for metal and ceramic part fabrication discussed in Chap. 5 and illustrated in Fig. 5.7. Stainless steel-bronze parts have been made with this technology [4]. The process is typically accurate to ±0.125 mm. Several ExOne machine models are also listed in Table 8.1.

Applications for the metal material models include prototypes of metal parts and some low-volume manufacturing, as well as tooling. As parts are fabricated in a powder bed, the surface finish of these parts is comparable to PBF parts. Finish machining is thus required for high tolerance and mating surfaces. ExOne markets another machine that fabricates gold dental restorations, for example, copings for crowns. The materials and binder printing system were developed specifically for this application, since higher resolution is needed.

In the tooling area, ExOne promotes the advantages of conformal cooling in injection molds. In conformal cooling, cooling channels are routed close to the surfaces of the part cavity, particularly where hot spots are predicted. Using conventional machining processes, cooling channels are drilled as straight holes. With AM processes, however, cooling channels of virtually any shape and configuration can be designed into tools. Figure 8.5 illustrates one tool design with conformal cooling channels that was fabricated in an ExOne machine.

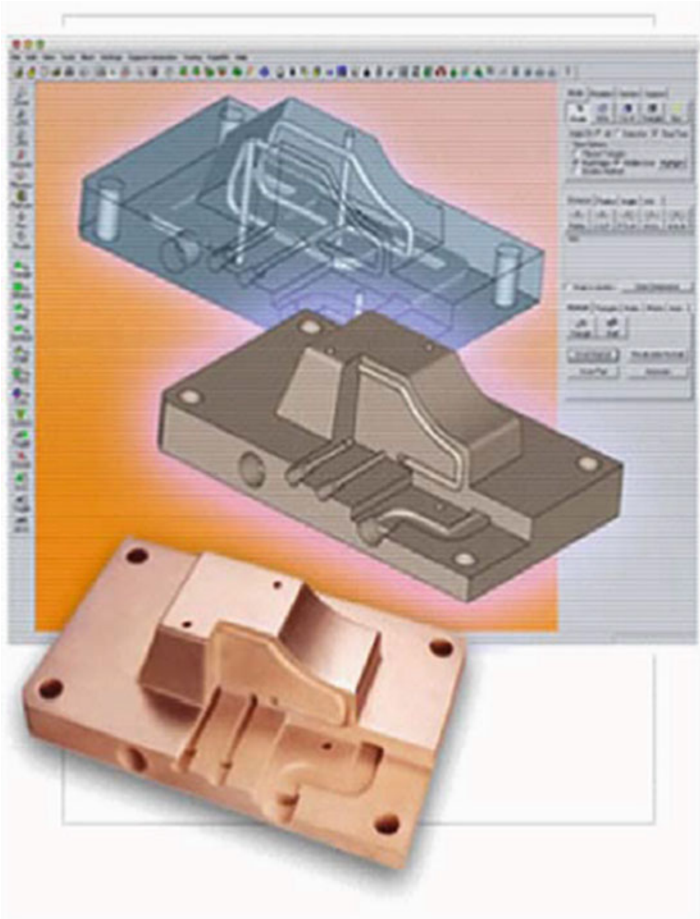

**Fig. 8.5** Injection mold with conformal cooling channels fabricated in an ExOne machine (Courtesy ExOne Company)

The largest machine, the S-Max, is intended for companies with large demands for castings, such as the automotive, heavy equipment, and oil & gas industries. A photo of the S-Max is shown in Fig. 8.6. Several dozen of these large machines (S-Max and its predecessor S15) have been installed. The machines print molds and cores for sand casting. Various metals can be cast into the printed molds, including aluminum, zinc, and even magnesium. Special equipment was developed for handling the large volumes of powders and heavy vats, including a silo and powder conveyor, conveyor track for transporting vats of powder and finished molds, and a debinding station. A typical installation with a S-Max or S15 machine occupies a room 40–50 $m^2$ in size.

Microjet Technology (Taiwan) is another company that currently markets BJ systems.


**Fig. 8.6** ExOne S-Max system (Courtesy ExOne)

## 8.5 Process Benefits and Drawbacks

The binder jetting processes share many of the advantages of material jetting relative to other AM processes. With respect to MJ, binder jetting has some distinct advantages. First, it can be faster since only a small fraction of the total part volume must be dispensed through the print heads. However, the need to distribute powder adds an extra step, slowing down binder processes somewhat. Second, the combination of powder materials and additives in binders enables material compositions that are not possible, or not easily achieved, using direct methods. Third, slurries with higher solids loadings are possible with BJ, compared with MJ, enabling better quality ceramic and metal parts to be produced. As mentioned earlier, BJ processes lend themselves readily to printing colors onto parts.

As a general rule, however, parts fabricated using BJ processes tend to have poorer accuracies and surface finishes than parts made with MJ. Infiltration steps are typically needed to fabricate dense parts or to ensure good mechanical properties.

As with any set of manufacturing processes, the choice of manufacturing process and material depends largely on the requirements of the part or device. It is a matter of compromising on the best match between process capabilities and design requirements.

## 8.6 Summary

The binder jetting processes share many of the advantages of material jetting relative to other AM processes. Compared to MJ, BJ has some distinct advantages. First, it can be faster since only a small fraction of the total part volume must be dispensed through the print heads. However, the need to recoat powder adds an extra step, slowing down binder processes somewhat. Second, the combination of powder materials and additives in binders enables material compositions that are not possible, or not easily achieved, using direct methods. Third, slurries with higher solids loadings are possible with BJ, compared with MJ, enabling better quality ceramic and metal parts to be produced. As mentioned earlier, BJ processes lend themselves readily to printing colors onto parts. Some novel machine architectures have been demonstrated using binder jetting technology that enable continuous printing, including spiral growth manufacturing and an architecture with a slanted build surface.

## 8.7 Exercises

1. Explain why support structures are not needed in the BJ process.
2. List several characteristics of a good binder material.
3. Identify several methods for achieving a high packing density in the powder bed.
4. Develop a build time model for a conventional binder jetting machine. Assume that the part platform is to be filled with parts and the platform is $L$ mm long and $W$ mm wide. The print head width is $H$ mm. Assume that a layer requires two passes of the print head, the print head can print in both directions of travel ($+X$ and $-Y$), and the layer thickness is $T$ mm. Figure 8.7 shows a schematic for the problem. Assume that a delay of D seconds is required for cleaning the print heads every $K$ layers. The height of the parts to be printed is $P$ mm. Assume that the powder bed recoater moves at 10 cm/s.
   (a) Develop a build time model using the variables listed in the problem statement. Compute the build time for a layer of parts given the variable values in the following table.

| | L | W | H | T | D | K | P |
|---|---|---|---|---|---|---|---|
| (b) | 300 | 185 | 50 | 0.04 | 10 | 20 | 60 |
| (c) | 300 | 185 | 50 | 0.028 | 12 | 25 | 85 |
| (d) | 260 | 250 | 60 | 0.015 | 12 | 25 | 60 |
| (e) | 340 | 340 | 60 | 0.015 | 12 | 25 | 60 |
| (f) | 490 | 390 | 60 | 0.015 | 12 | 25 | 80 |

5. Modify the build time model for the continuous printing Voxeljet machine.

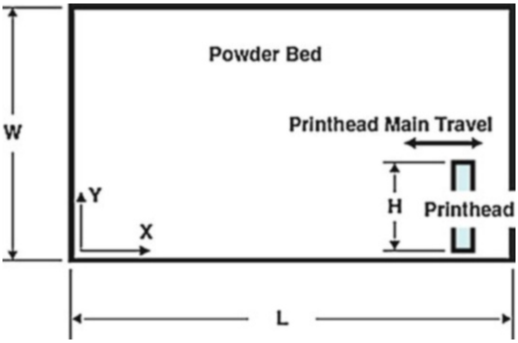


**Fig. 8.7** Schematic for problems 4–5

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