TOWARD MANUFACTURING OF FINE COMPONENTS BY 3D PRINTING

E. Sachs[1], B. Polito[1], D. Ables[1], M. Cima[2]
[1]Department of Mechanical Engineering
[2]Department of Materials Science
Massachusetts Institute of Technology, Cambridge, MA 02139

and

Hiroyasu Tsuchiya, Yasushi Enokido
TDK Corporation

Abstract

Solid Freeform Fabrication has earned its place in the industrial practice of prototyping and is beginning to have an impact in the fabrication of tooling. The next and perhaps greatest opportunity for SFF lies on the direct manufacture of components. This paper will present efforts directed toward the MANUFACTURE IN HIGH QUANTITY of small, precision components by 3D Printing. The primary focus is on ceramic and ceramic/metal components, although all metal components are envisioned as well.

The production of small, fine-featured parts presents two opportunities for a new machine architecture. First, the powderbeds required for small parts are themselves small and lightweight. Thus, a machine can be designed where powderbeds move from the layer spreading station to the print station and back again. Multiple powder beds can be in play, taking full advantage of all stations of the machine. The second opportunity is to define the perimeter of the part using vector motions of a nozzle with the interior filled by raster scanning. Such an approach has the advantage that the boundary of the part will be defined as a smooth contour.

Moving powderbeds and vector printing are combined in the linear shuttle-type machine for research purposes. Ultimately, a rotary machine is envisioned for high production.

Manufacturing vs. Prototyping

The challenges that have been met by Solid Freeform Fabrication technologies in creating useful prototypes are considerable. However, in many respects there is more leeway in the fabrication of prototypes than in the direct manufacture of components. The direct manufacture of components must be accomplished at a rate that is sufficient, given the economics of the application. Thus, for example, some processes for the direct laser fabrication of metal components might take 20 hours to create one liter of metal component. A component made at this rate might be an extremely useful prototype, but is unlikely to be useful in a manufacturing context. Further, while extensive secondary operations might be tolerable in improving the quality of a prototype part, manufacturing demands an absolute minimum of secondary operations. Thus, for example, if the entire surface of a part made by Solid Freeform Fabrication must be subjected to extensive finishing, the process may be uneconomic for manufacturing, although acceptable for prototyping. Another significant challenge is that of material properties.

While reductions in the performance of materials or variation in material properties might be acceptable in a prototype, manufactured components will always carry more stringent demands. The true challenge of manufacturing by Solid Freeform Fabrication is that a process must *simultaneously* achieve the requisite fabrication rate and quality, including issues of dimensions, surface finish and material properties. It would be of little use to achieve the requisite quality but at an unacceptable rate, or to achieve the requisite rate but at an unacceptable quality. Thus, for example, if a strategy is pursued to increase the build rate of a particular Solid Freeform Fabrication process, it must also preserve the quality of the components made.

Machine Architectures

There are two primary machine architectures under development for manufacturing applications. The stationary powderbed, raster print architecture is suitable to medium and large parts. The moving powderbed, vector print architecture is suited to fine-scaled, small parts. These architectures are described below.

Stationary Powderbed, Raster Printing

Figure 1 shows a plan view of the MIT "Alpha" machine. In this machine, the powderbed is fixed at the center of the machine and the elements of the machine move to and from the

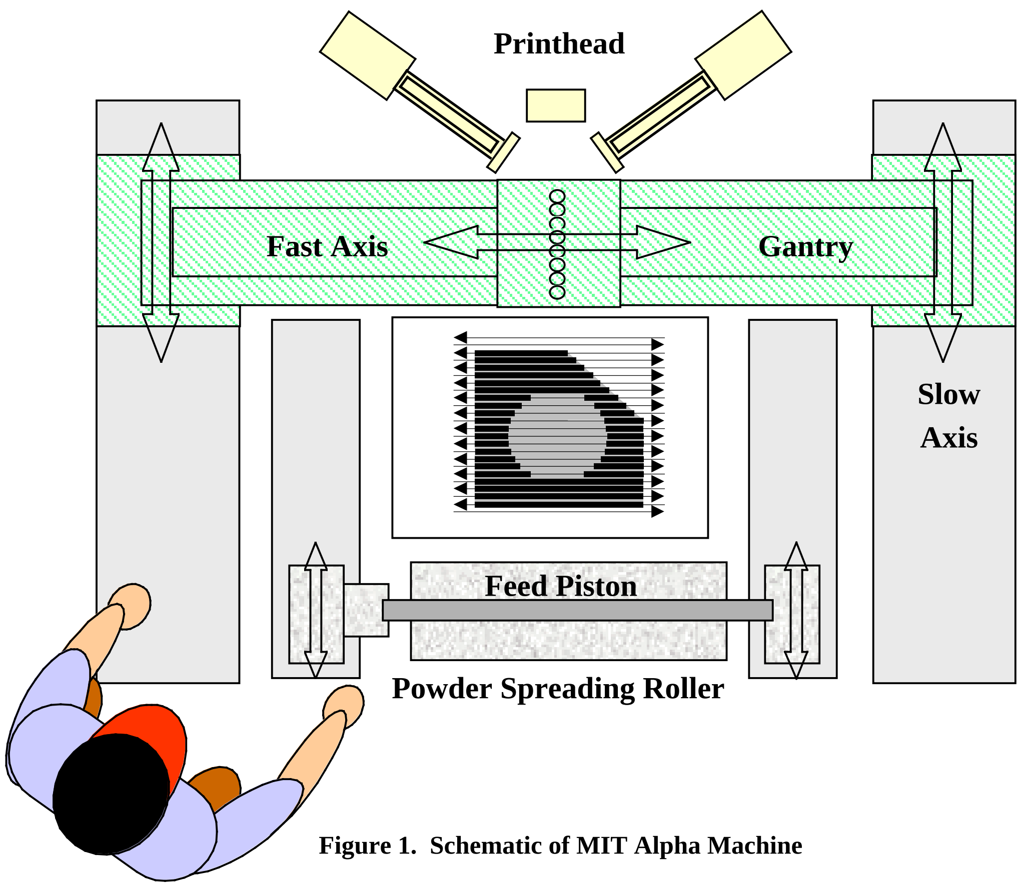

Figure 1. Schematic of MIT Alpha Machine

Figure 2. The RTS-300 machine for 3-D Printing of metal tooling and metal parts of ExtrudeHone Corp., of Irwin, PA. This machine has a build volume of 300 x 300 x 250mm.

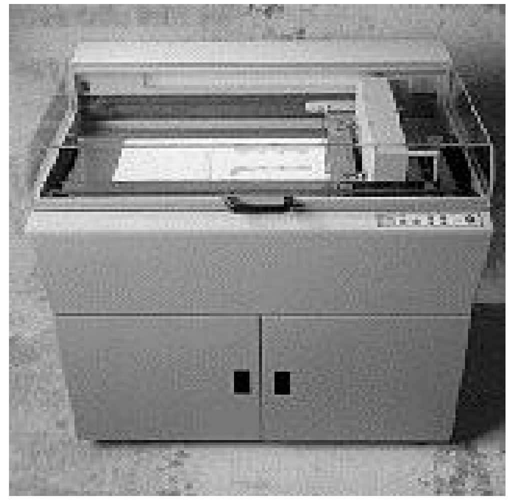

Figure 3. Three Dimensional Printing machine of Z Corp., Burlington, MA.

powderbed. As shown in figure 1, the powder spreading gantry is independent of the print gantry and powder spreading takes place while the printhead is being inspected. After spreading, the spread gantry retracts and the print gantry advances to address the powderbed. The only motion of the powderbed is to increment downward to allow for each new layer to be spread. The stationary bed makes sense for this machine, as the powderbeds can be quite large and massive, especially when filled with metal powders. The printhead used in this type of machine is composed of a linear array of nozzles, which is raster-scanned over the surface of the powder. A highly schematic raster-printed part is shown in the powderbed in figure 1. The stationary bed, raster print machine has taken several commercial forms, including those marketed by Z Corp of Burlington, MA and ExtrudeHone of Irwin, PA (see figures 2 and 3). These machines use different inkjet printhead technology, however both make use of raster scanning of the printheads.

The fundamental strength of the stationary powderbed, raster print machine is that it can be scaled up in size and rate. For example, ExtrudeHone (with contributions from MIT) is currently building a scaled-up machine, which will print over an area of 500 x 1000mm, using a printhead composed of a linear array of 96 jets. This printhead will deliver approximately 120 cc/minute of binder, corresponding to the delivery of approximately 3.5 million droplets per second. The machine will be capable of creating over 3500 cc per hour of parts and/or tooling in high resolution mode, and over 10,000 cc per hour in high speed mode (with slightly lower resolution). In high speed mode, a single machine could produce aver 400,000 green components of 50 x 50 x 50mm size in one year in 3 shift operation, for example (parts may be stacked vertically in the bed). Any number of different component geometries could be produced, including in a single build.

Moving Powderbed, Vector Print Architecture

An important class of components are small, fine-featured parts to be made in large quantity. Figure 4 shows a green stainless steel part made with -20μm powder and 50μm layers. Figure 5

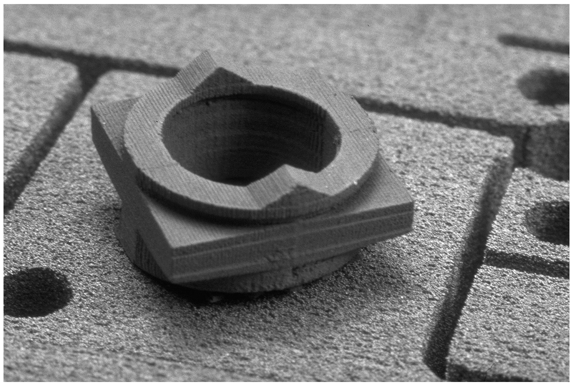

Figure 4. A stainless steel green part made of -20μm powder, using 50μm layers. The component is 10mm on a side. The component is sitting on top of a 3D printed part, which is made with 60μm powder.

Figure 5. A set of ceramic parts made by 3D Printing. The spools in the lower left-hand corner are approximately 3mm tall.

shows a set of green and fired parts made of barium titanate powder. Figure 6 shows a set of fired alumina parts made with 1μm and 50μm layers.

The fabrication of multiple copies of small components provides yet another opportunity for a significant change in machine architecture. Whereas the powderbeds in a raster machine can be quite massive, the powderbeds for making fine components are much smaller. This opens up the opportunity for moving the powderbeds from one station to another, rather than having a stationary powderbed, around which the various components of the machine must move. In the future, one can envision a rotary-style machine, such as that illustrated in figure 7, where the powder spreading, binder printing, drying and inspection stations are at fixed positions around a

Figure 6. 1μm alumina parts (fired)

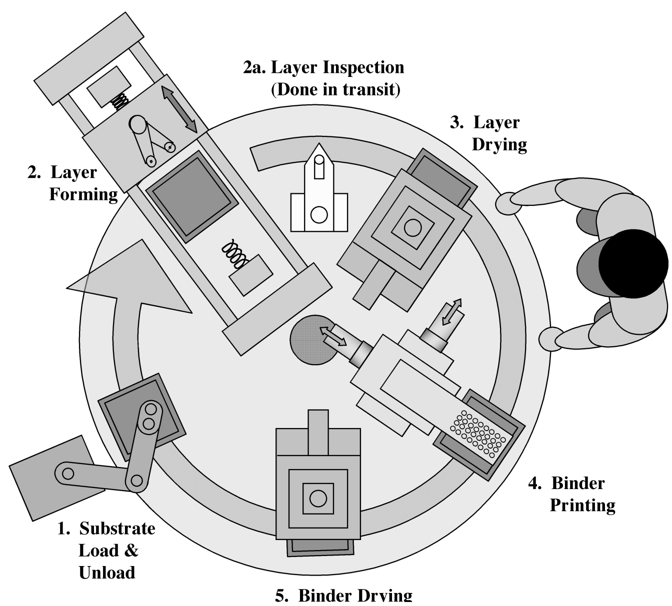

Figure 7. Moving bed, vector print schematic.

rotary table and powderbeds are indexed from one station to another by the rotary table. Multiple powder beds can be in play at any one time, and multiple parts can be printed into each powderbed, as many as can fit in the powderbed. The components within a given powderbed are likely to all be the same; however, the components from one powderbed to another can be different in geometry. A given powderbed would go around the rotary machine once per layer, thus a component made of 100 layers would go around 100 times and then come off the machine at the unload/load station. Moving the powderbeds has the key advantages of allowing more freedom in the design of the various stations, especially the powder spreading and printing stations, and making efficient use of these stations as they will be in use most of the time (as opposed to a stationary powderbed machine, where they are idle at least half of the time).

In the moving powderbed, vector machine architecture, the perimeter of a part is described by tracing an inkjet printhead in a vector motion, thereby providing a smooth description of the outline. While vector description of the outline is impractical for large parts, the small parts

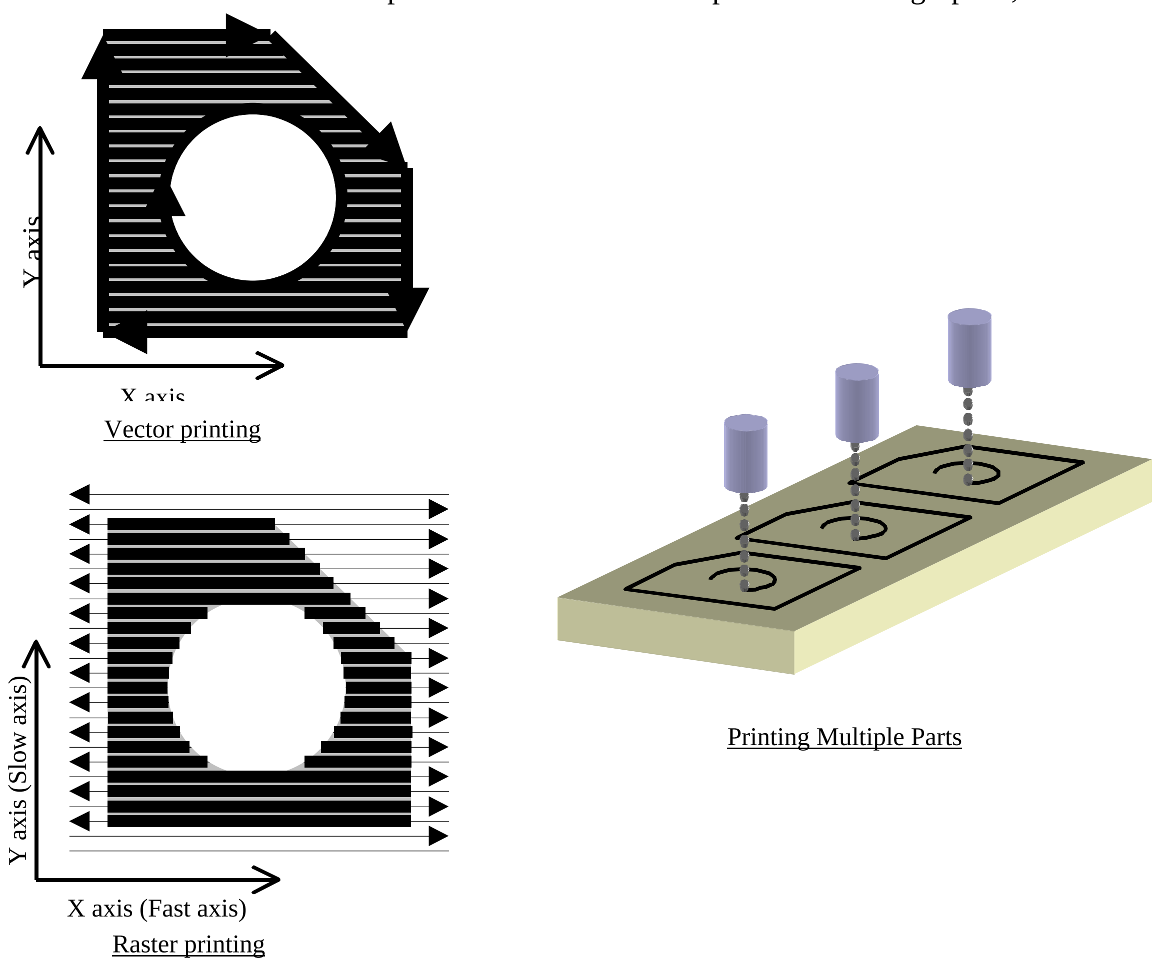

Figure 8. Vector printing of the outline of a part, as illustrated in the upper left hand drawing is a good approach to high quality parts, when the parts are small in size. On the right is an illustration of simultaneous printing of three identical parts, each addressed by its own individual ink-jet.

under consideration for this machine architecture can be vector outlined in reasonable time. The interior of the geometry is then filled by raster scanning. In the machine architecture under development, a single nozzle is used to address each part. Multiple, identical parts can be made simultaneously through the use of a platen with multiple individual nozzles, which are moved simultaneously to describe the parts. Figure 8 illustrates this concept with three nozzles, each of which is addressing an individual part. This multiplicity can be extended to a two dimensional array of nozzles as well. The nozzles would be fixed in a platen, and the entire platen would be moved first to describe the vector outline and then to describe the raster fill. This approach to the use of multiple nozzles has a distinct advantage over the raster machine approach, when applied to the creation of multiple copies of small parts:

- As noted above, the perimeter of the parts is described by a smooth motion, thereby resulting in good surface finish.
- Since each part is addressed by its own nozzle, the precise spacing and alignment of the nozzles with respect to one another is immaterial.
- If a nozzle fails during production, the result will be one failed part. However, if a single nozzle fails in a raster machine, it will affect all parts that are scanned by that nozzle.

The vector architecture demands a different type of printhead from that used in the continuous jet machine as described above. In particular, the vector outline of a part is best described using motions, which involve changes in speed. For example, if a perfect square were to be described, the printhead would start at one corner, accelerate to the middle of the side, and then begin to decelerate, in order to stop at the next corner. A constant velocity of traverse would necessarily result in overshoot at the corners, due to the limited accelerations possible by the servo motor system, which controls the trajectory of the nozzles. Thus, the appropriate printhead must be capable of operation at a wide range of frequencies bound to a generation of single droplets. The appropriate class of inkjet printing is called “drop-on-demand” (DoD). In such a printhead, a single drop is emitted every time an electrical pulse is sent to the printhead. A single nozzle

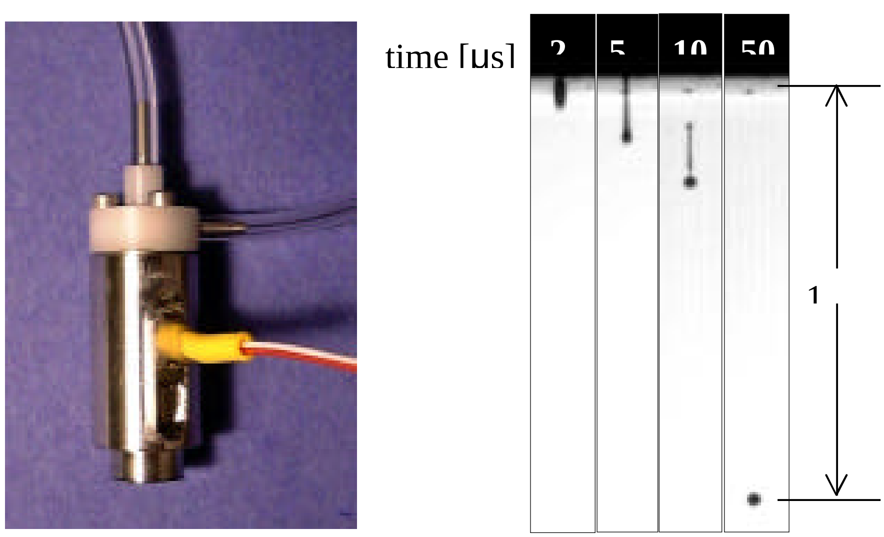

Figure 9. A photograph of a single nozzle drop-on-demand printhead and some strobe images of the formation of a droplet from that printhead.

printhead is under development at MIT and is shown in figure 9. In this printhead, a cylindrical piezo ceramic contracts when a pulse is applied and essentially squirts out a droplet of the binder material. A sequence of droplet emission is shown in figure 9. This printhead design can operate comfortably between single drop formation and formation of drops up to 3 kHz.

The single nozzle vector machine architecture is most appropriate to the fabrication of fine detailed small parts. An estimate of the time required to print a single layer can be had by separately estimating the time required to trace the vector outline and the time required to raster fill the interior. Under the assumptions of maximum drop rates of 3 kHz, maximum printhead accelerations of 1 g and maximum table traverse rates of .3 m/s, the time required to print a 1cm x 1cm square component would consist of 0.4 seconds to define the vector outline and 13. seconds to raster fill the geometry, for a total of 13.4 seconds per layer. To give some sense of scaling, the time that would be needed for a component, which is 5mm x 5mm is 5 seconds per layer, and a component which is 15mm x 15mm would take 25 seconds per layer.

The production rate of a future rotary machine can be quite reasonable. For example, consider a machine with 5 powderbeds, each with 200 identical parts in it. The parts are 5 x 5 x 5 mm in size. The parts are built with 50 micron layers and so, 100 layers are required. The time at each station is 15 seconds and 1 second is required to increment the index table from station to station. The total time for one revolution of the table is therefore 80 seconds. On average, after 100 revolutions (8000 seconds), 1000 parts are fabricated. Thus, a part is fabricated every 8 seconds, on average. In a 3-shift operation of 6000 hours, 2,700,000 parts can be fabricated. As a first step toward a rotary machine based on moving powderbeds, a linear version is now being

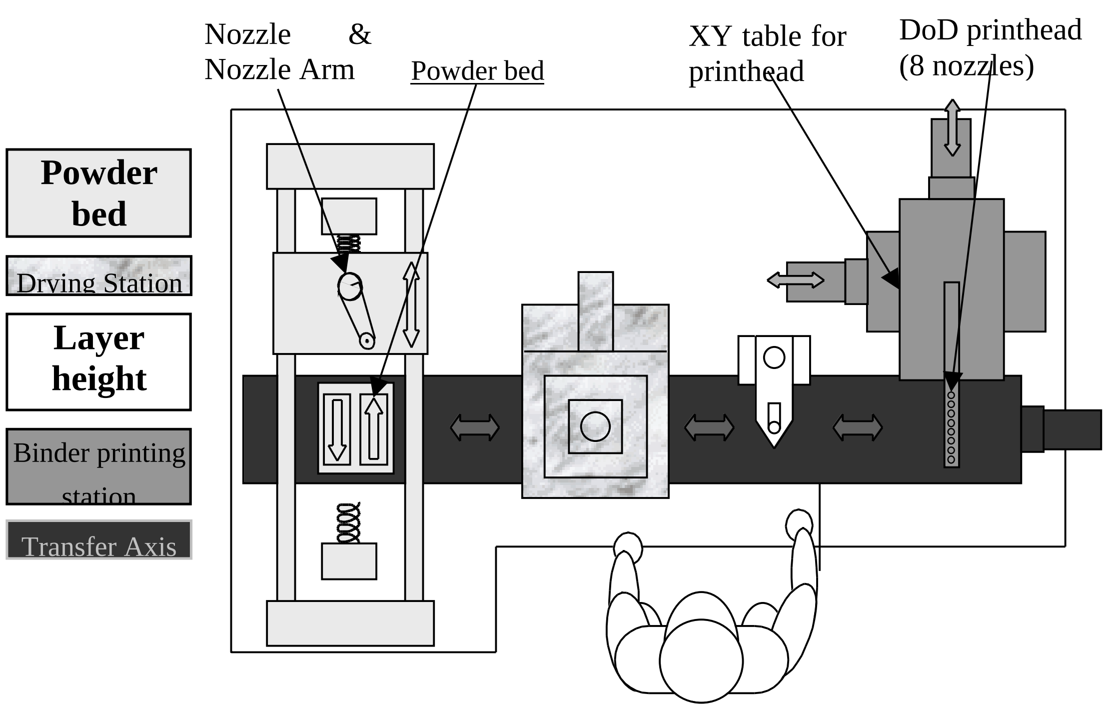

Figure 10. A schematic of the linear machine that has been built for prototyping of small parts by 3D Printing. This machine is a stepping stone to the full rotary machine illustrated in figure 7.

completed in a joint effort between TDK Corp. and MIT. Figure **10** shows schematically this

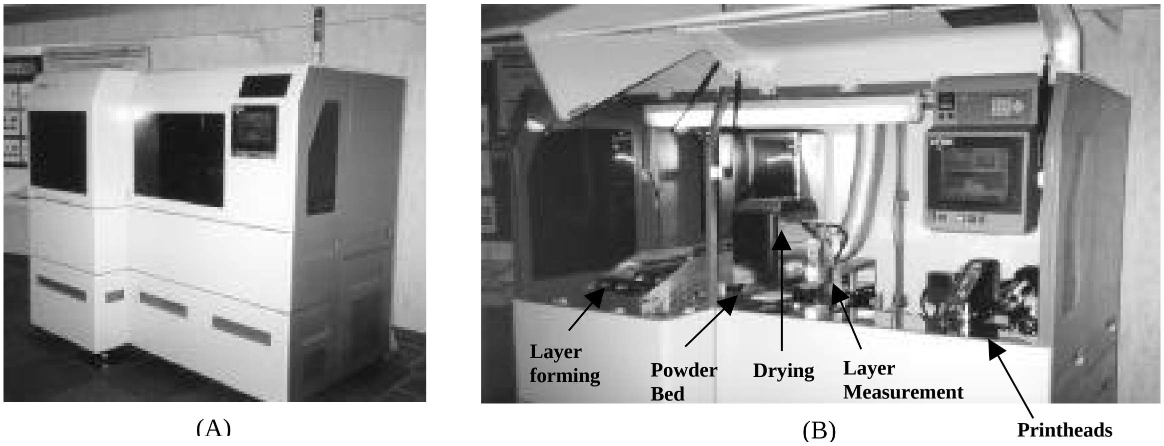

Figure 11. Linear Moving Bed, Vector Print machine built jointly by TDK and MIT, with hood closed (A) and with hood open (B).

linear version, where a single powder bed will be shuttled back and forth between the various stations. This machine is simpler to build and will allow us to prove out ost of the concepts involved in the moving powderbed machine. Figure 11 shows two views of the machine itself.

Conclusion

In the development of 3D Printing, the primary machine architecture has been that of a stationary powderbed with raster printing. In this machine architecture, used by MIT and by licensees commercializing 3D Printing, the powderbed is large and often massive, and remains fixed in the machine. The elements of the machine, specifically the powder spreading and the binder printhead, move to and from this stationary powderbed. Binder printing is accomplished by a raster motion of the linear array of nozzles. This type of machine is well-suited to the fabrication of medium and large parts.

An important class of components is that of the small, fine-featured component, whether metal or ceramic, or metal/ceramic. Such components are generally smaller than 10mm on a side and may be as small as 1mm. The fabrication of multiple copies of such fine-featured parts presents two characteristics, which lead to the definition of a new machine architecture for 3D Printing. First, the powderbeds in which these parts are fabricated are small and lightweight. As a consequence, the powderbeds can be moved from station to station within the machine, rather than having the stations move to the powderbeds. A rotary machine can be envisioned, where the powderbeds are mounted on an index table and the index table goes through one rotation for each layer that is fabricated. Such a rotary machine makes efficient use of each station as the stations are in use at all times, except when the index table is moving. Such a rotary machine can also be easily adapted to factory automation, as one of the stations can be a robotic load/unload. The second distinguishing feature of small parts is that the perimeter is short. For this reason, it is practical to define the perimeter of the part using a vector tracing, followed by a raster fill of the interior. This approach can lead to improved surface finish. In order to support he use of vector printing, drop-on-demand printing must be used where a drop is emitted from the nozzle for each pulse applied. Drop-on-demand printhead can be operated at variable frequency, thus allowing one to match the velocity of traverse of the vector outline. Finally, multiple parts will be fabricated with a two-dimensional array of nozzles. Each nozzle will address one and only one part. This has the advantage of making the machine insensitive to registration between nozzles. A further advantage is that the failure of a single nozzle will affect one and only one part.

As a first step toward a high production rotary machine, MIT and TDK have jointly built a linear/shuttle machine. This machine will be used to prove out the concepts behind the moving powderbed, vector print machine architecture.

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