# Chapter 2
# Development of Additive Manufacturing Technology

**Abstract** It is important to understand that AM was not developed in isolation from other technologies. It would not be possible for AM to exist were it not for innovations in areas like 3D graphics and Computer-Aided Design software. This chapter highlights some of the key moments that catalogue the development of Additive Manufacturing. It describes how the different technologies converged to a state where they could be integrated into AM machines. It will also discuss milestone AM technologies and how they have contributed to increase the range of AM applications. Furthermore, we will discuss how the application of Additive Manufacturing has evolved to include greater functionality and embrace a wider range of applications beyond the initial intent of prototyping.

## 2.1 Introduction

Additive Manufacturing (AM) came about as a result of developments in a variety of technology sectors. Like with many manufacturing technologies, improvements in computing power and reduction in mass storage costs paved the way for processing the large amounts of data typical of modern 3D Computer-Aided Design (CAD) models within reasonable time frames. Nowadays, we have become quite accustomed to having powerful computers and other complex automated machines around us, and sometimes it may be difficult for us to imagine how the pioneers struggled to develop the first AM machines.

This chapter highlights some of the key moments that catalogue the development of Additive Manufacturing technology. It will describe how the different technologies converged to a state where they could be integrated into AM machines. It will also discuss milestone AM technologies. Furthermore, we will discuss how the application of Additive Manufacturing has evolved to include greater functionality and embrace a wider range of applications beyond the initial intention of just proto-



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typing. We close the chapter with a summary of standards that have been developed to support the adoption of AM.

## 2.2 Computers

Like many other technologies, AM came about as a result of the invention of the computer. However, there was little indication that the first computers built in the 1940s (like the Zuse Z3 [1], ENIAC [2], and EDSAC [3] computers) would change lives in the way that they so obviously have. Inventions like the thermionic valve, transistor, and microchip made it possible for computers to become faster, smaller, and cheaper with greater functionality. This development has been so quick that even Bill Gates of Microsoft was caught off guard when he thought in 1981 that 640 kb of memory would be sufficient for any Windows-based computer. In 1989, he admitted his error when addressing the University of Waterloo Computer Science Club [4]. Similarly in 1977, Ken Olsen of Digital Electronics Corp. (DEC) stated that there would never be any reason for people to have computers in their homes when he addressed the World Future Society in Boston [5]. That remarkable misjudgment may have caused Olsen to lose his job not long afterward.

One key to the development of computers as serviceable tools lies in their ability to perform tasks in real time. In the early days, serious computational tasks took many hours or even days to prepare, run, and complete. This served as a limitation to everyday computer use, and it is only since it was shown that tasks can complete in real time that computers have been accepted as everyday items rather than just for academics or big business. This has included the ability to display results not just numerically but graphically as well. For this we owe a debt of thanks at least in part to the gaming industry, which has pioneered many developments in graphics technology with the aim to display more detailed and more "realistic" images to enhance the gaming experience.

AM takes full advantage of many of the important features of computer technology, both directly (in the AM machines themselves) and indirectly (within the supporting technology), including:

- *Processing power*: Part data files can be very large and require a reasonable amount of processing power to manipulate while setting up the machine and when slicing the data before building. Earlier machines would have had difficulty handling large CAD data files.
- *Graphics capability*: AM machine operation does not require a big graphics engine except to see the file while positioning within the virtual machine space. However, all machines benefit from a good graphical user interface (GUI) that can make the machine easier to set up, operate, and maintain.
- *Machine control*: AM technology requires precise positioning of equipment in a similar way to a Computer Numerical Controlled (CNC) machining center or even a high-end photocopy machine or laser printer. Such equipment requires controllers that take information from sensors for determining status and actuators for positioning and other output functions. Computation is generally required

in order to determine the control requirements. Conducting these control tasks even in real time does not normally require significant amounts of processing power by today's standards. Dedicated functions like positioning of motors, lenses, etc. would normally require individual controller modules. A computer would be used to oversee the communication to and from these controllers and pass data related to the part build function.

- *Networking*: Nearly every computer these days has a method for communicating with other computers around the world. Files for building would normally be designed on another computer to that running the AM machine. Earlier systems would have required the files to be loaded from disk or tape. Nowadays almost all files will be sent using an Ethernet connection, often via the Internet.
- *Integration*: As is indicated by the variety of functions, the computer forms a central component that ties different processes together. The purpose of the computer would be to communicate with other parts of the system, to process data, and to send that data from one part of the system to the other. Figure 2.1 shows how the abovementioned technologies are integrated to form an AM machine.

Earlier computer-based design environments required physically large mainframe and mini computers. Workstations that generally ran the graphics and input/output functions were connected to these computers. The computer then ran the complex calculations for manipulating the models. This was a costly solution based around the fact that the processor and memory components were very expensive elements. With the reduction in the cost of these components, personal computers

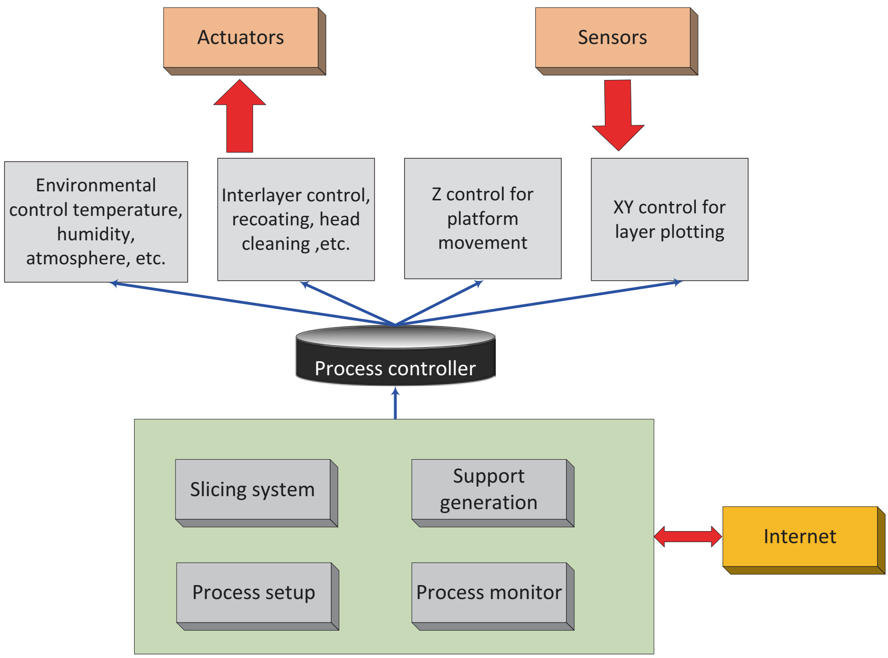


**Fig. 2.1** General integration of an AM machine

(PCs) became viable solutions. Earlier PCs were not powerful enough to replace the complex functions that workstation-based computers could perform, but the speedy development of PCs soon overcame all but the most computationally expensive requirements.

Without computers there would be no capability to display 3D graphic images. Without 3D graphics, there would be no 3D Computer-Aided Design. Without this ability to represent objects digitally in 3D, we would have a limited desire to use machines to fabricate anything but the simplest shapes. It is safe to say, therefore, that without the computers we have today, we would not have seen Additive Manufacturing develop.

## 2.3 Computer-Aided Design Technology

Today, every engineering student must learn how to use computers for many of their tasks, including the development of new designs. CAD technologies are available for assisting in the design of large buildings and of nano-scale microprocessors. CAD technology holds within it the knowledge associated with a particular type of product, including geometric, electrical, thermal, dynamic, and static behavior. CAD systems may contain rules associated with such behaviors that allow the user to focus on design and functionality without worrying too much whether a product can or cannot work. CAD also allows the user to focus on small features of a large product, maintaining data integrity and ordering it to understand how subsystems integrate with the remainder.

Additive Manufacturing technology primarily makes use of the output from 3D solid modeling CAD software. It is important to understand that this is only a branch of a much larger set of CAD systems and, therefore, not all CAD systems will produce output suitable for layer-based AM technology. Currently, AM technology focuses on reproducing geometric form, and so the better CAD systems to use are those that produce such forms in the most precise and effective way.

Early CAD systems were extremely limited by the display technology. The first display systems had little or no capacity to produce anything other than alphanumeric text output. Some early computers had specialized graphic output devices that displayed graphics separate from the text commands used to drive them. Even so, the geometric forms were shown primarily in a vector form, displaying wire-frame output. As well as the heavy demand on the computing power required to display the graphics for such systems, this was because most displays were monochrome, making it very difficult to show 3D geometric forms on screen without lighting and shading effects.

CAD would not have developed so quickly if it were not for the demands set by computer-aided manufacturing (CAM). CAM represents a channel for converting the virtual models developed in CAD into the physical products that we use in our everyday lives. It is doubtful that without the demands associated with this conversion from virtual to real that CAD would have developed so far or so quickly. This, in turn, was fueled and driven by the developments in associated technologies, like processor, memory, and display technologies. CAM systems produce the code for numerically controlled (NC) machinery, essentially combining coordinate data with commands to select and actuate the cutting tools. Early NC technologies would take CAM data relating to the location of machined features, like holes, slots, pockets, etc. These features would then be fabricated by machining from a stock material. As NC machines proved their value in their precise, automated functionality, so the sophistication of the features increased. This has now extended to the ability to machine highly complex, freeform surfaces. However, there are two key limitations to all NC machining:

- Almost every part must be made in stages, often requiring multiple passes for material removal and setups.
- All machining is performed from an approach direction (sometimes referred to as 2.5D rather than fully 3D manufacture). This requires that the stock material be held in a particular orientation and that not all the material can be accessible at any one stage in the process.

NC machining, therefore, only requires surface modeling software. All early CAM systems were based on surface modeling CAD. AM technology was the first automated computer-aided manufacturing process that truly required 3D solid modeling CAD. It was necessary to have a fully enclosed surface to generate the driving coordinates for AM. This can be achieved using surface modeling systems, but because surfaces are described by boundary curves, it is often difficult to precisely and seamlessly connect these together. Even if the gaps are imperceptible, the resulting models may be difficult to build using AM. At the very least, any inaccuracies in the 3D model would be passed on to the AM part that was constructed. Early AM applications often displayed difficulties because of associated problems with surface modeling software.

Since it is important for AM systems to have accurate models that are fully enclosed, the preference is for solid modeling CAD. Solid modeling CAD ensures that all models made have a volume and, therefore, by definition are fully enclosed surfaces. While surface modeling can be used in part construction, we cannot always be sure that the final model is faithfully represented as a solid. Such models are generally necessary for computer-aided engineering (CAE) tools like finite element analysis (FEA) but are also very important for other CAM processes.

Most CAD systems can now quite readily run on PCs. This is generally a result of the improvements in computer technology mentioned earlier but is also a result in improvements in the way CAD data is presented, manipulated, and stored. Most CAD systems utilize non-uniform rational basis splines or NURBS [6]. NURBS are an excellent way of precisely defining the curves and surfaces that correspond to the outer shell of a CAD model. Since model definitions can include freeform surfaces as well as simple geometric shapes, the representation must accommodate this, and splines are complex enough to represent such shapes without making the files too large and unwieldy. They are also easy to manipulate to modify the resulting shape.

CAD technology has rapidly improved along the following lines:

- *Realism*: With lighting, shading effects, ray tracing, and other photorealistic imaging techniques, it is becoming possible to generate images of the CAD models that are difficult to distinguish from actual photographs. In some ways, this reduces the requirements on AM models for visualization purposes.
- *Usability and user interface*: Early CAD software required the input of text-based instructions through a dialog box. Development of Windows-based graphical user interfaces (GUIs) has led to graphics-based dialogs and even direct manipulation of models within virtual 3D environments. Instructions are issued through the use of drop-down menu systems and context-related commands. To suit different user preferences and styles, it is often possible to execute the same instruction in different ways. Keyboards are still necessary for input of specific measurements, but the usability of CAD systems has improved dramatically. There is still some way to go to make CAD systems available to those without engineering knowledge or without training, however.
- *Engineering content*: Since CAD is almost an essential part of a modern engineer's training, it is vital that the software includes as much engineering content as possible. With solid modeling CAD, it is possible to calculate the volumes and masses of models, to investigate fits and clearances according to tolerance variations, and to export files with mesh data for finite element analysis. FEA is often even possible without having to leave the CAD system.
- *Speed*: As mentioned previously, the use of NURBS assists in optimizing CAD data manipulation. CAD systems are constantly being optimized in various ways, mainly by exploiting the hardware developments of computers.
- *Accuracy*: If high tolerances are expected for a design, then it is important that calculations are precise. High precision can make heavy demands on processing time and memory.
- *Complexity*: All of the above characteristics can lead to extremely complex systems. It is a challenge to software vendors to incorporate these features without making them unwieldy and unworkable.
- *Usability*: Recent developments in CAD technology have focused on making the systems available to a wider range of users. In particular the aim has been to allow untrained users to be able to design complex geometry parts for themselves. There are now 3D solid modeling CAD systems that run entirely within a web browser with similar capabilities to workstation systems of only 10 years ago.

Many CAD software vendors are focusing on producing highly integrated design environments that allow designers to work as teams and to share designs across different platforms and for different departments. Industrial designers must work with sales and marketing, engineering designers, analysts, manufacturing engineers, and many other branches of an organization to bring a design to fruition as a product. Such branches may even be in different regions of the world and may be part of the same organization or acting as subcontractors. The Internet must therefore also be integrated with these software systems, with appropriate measures for fast and accurate transmission and protection of intellectual property.

**Fig. 2.2** A CAD model on the left converted into STL format on the right

It is quite possible to directly manipulate the CAD file to generate the slice data that will drive an AM machine, and this is commonly referred to as direct slicing [7]. However, this would mean every CAD system must have a direct slicing algorithm that would have to be compatible with all the different types of AM technology. Alternatively, each AM system vendor would have to write a routine for every CAD system. Both of these approaches are impractical. The solution is to use a generic format that is specific to the technology. This generic format was developed by 3D Systems, USA, who was the first company to commercialize AM technology and called the file format "STL" after their stereolithography technology (an example of which is shown in Fig. 2.2).

The STL file format was made public domain to allow all CAD vendors to access it easily and hopefully integrate it into their systems. This strategy has been successful, and STL is now a standard output for nearly all solid modeling CAD systems and has also been adopted by AM system vendors [8]. STL uses triangles to describe the surfaces to be built. Each triangle is described as three points and a facet normal vector indicating the outward side of the triangle, in a manner similar to the following:

*facet normal* − 4.470293E−02 7.003503E−01 − 7.123981E-01,
*outer loop,*
*vertex* − 2.812284E+00 2.298693E+01 0.000000E+00,
*vertex* − 2.812284E+00 2.296699E+01−1.960784E−02,
*vertex* − 3.124760E+00 2.296699E+01 0.000000E+00,
*endloop,*
*endfacet.*

The demands on CAD technology in the future are set to change with respect to AM. As we move toward more and more functionality in the parts produced by AM, we must understand that the CAD system must include rules associated with AM. To date, the focus has been on the external geometry. In the future, we may need to know rules associated with how the AM systems function so that the output can be optimized.

## 2.4 Other Associated Technologies

Aside from computer technology, there are a number of other technologies that have developed along with AM that are worthy of note here since they have served to contribute to further improvement of AM systems.

### *2.4.1 Printing Technologies*

Inkjet and droplet printing technologies have rapidly developed in recent years. Improvements in resolution and reduction in costs has meant that high-resolution printing, typically with multiple colors, is available as part of our everyday lives. Such improvement in resolution has also been supported by improvement in material handling capacity and reliability. Initially, colored inks were low viscosity and fed into the print heads at ambient temperatures. Now it is possible to generate much higher pressures within the droplet formation chamber so that materials with much higher viscosity and even molten materials can be printed. This means that droplet deposition can now be used to print photocurable and molten resins as well as binders for powder systems. Since print heads are relatively compact devices with all the droplet control technology highly integrated into these heads (like the one shown in Fig. 2.3), it is possible to produce low-cost, high-resolution, high-throughput AM technology.

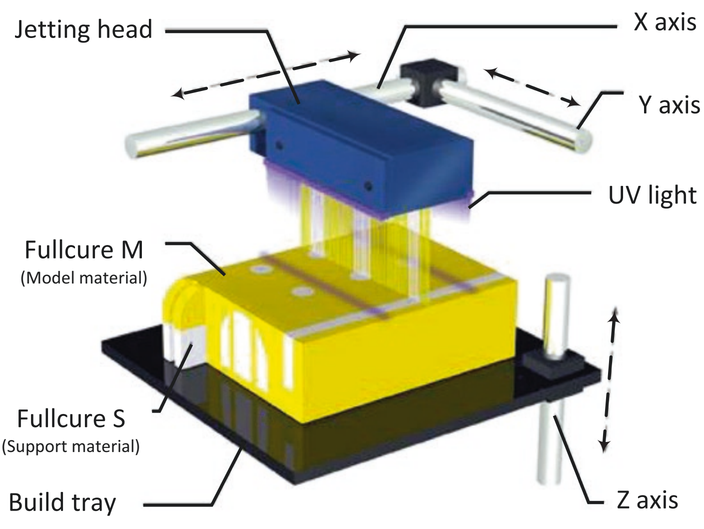


**Fig. 2.3** Printer technology used on an AM machine**.** (Photo courtesy of Objet)

### 2.4.2 Programmable Logic Controllers

The input CAD models for AM are large data files generated using standard computer technology. Once they are on the AM machine, however, these files are reduced to a series of process stages that require sensor input and signaling of actuators. This process and machine control is often best carried out using microcontroller systems rather than microprocessor systems. Industrial microcontroller systems form the basis of programmable logic controllers (PLCs), which are used to reliably control industrial processes. Designing and building industrial machinery, like AM machines, are much easier using building blocks based around modern PLCs for coordinating and controlling the various steps in the machine process.

### 2.4.3 Materials

Early AM technologies were built around materials that were already available and that had been developed to suit other processes. However, AM processes are somewhat unique, and these original materials were far from ideal for these new applications. For example, the early photocurable resins resulted in models that were brittle and that warped easily. Powders used in Laser-Based Powder Bed Fusion (LB-PBF) processes degraded quickly within the machine, and many of the materials resulted in parts that were quite weak. As we came to understand the technology better, materials were developed specifically to suit AM processes. Materials have been tuned to suit more closely the operating parameters of the different processes and to provide better output parts. As a result, parts are now much more accurate, stronger, and longer lasting. In turn, these new materials have resulted in the processes being tuned to produce higher-temperature materials (including metals), smaller feature sizes, and faster throughput.

### 2.4.4 Computer Numerically Controlled Machining

One of the reasons AM technology was originally developed was because CNC technology was not able to produce satisfactory output within the required time frames. CNC machining was slow, cumbersome, and difficult to operate. AM technology on the other hand was quite easy to set up with quick results but had poor accuracy and limited material capability. As improvements in AM technologies came about, vendors of CNC machining technology realized that there was now growing competition. CNC machining has dramatically improved, just as AM technologies have matured. It could be argued that high-speed CNC would have developed anyway, but some have argued that the perceived threat from AM technology caused CNC machining vendors to rethink how their machines were made. The combination of high-speed machining and AM for certain applications, such as for

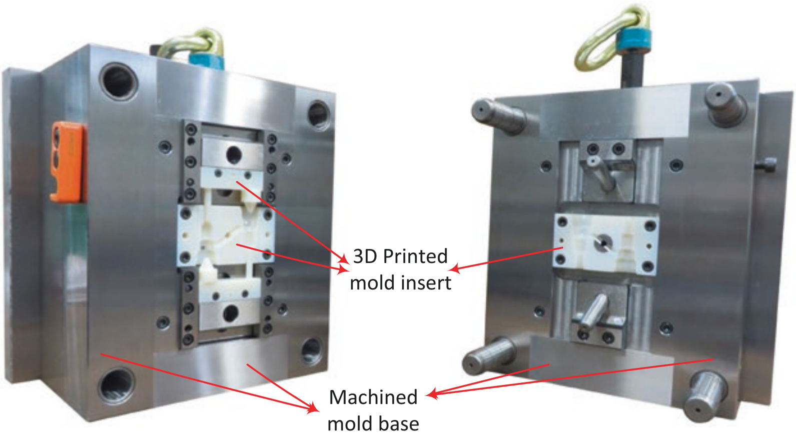


**Fig. 2.4** Standardized mold system and 3D printed mold inserts permitting rapid, low-cost prototypes. (Photo courtesy of HASCO) [10]

making large, complex, and durable molds for standardized mold system (plastic injection molding), as shown in Fig. 2.4 [9], illustrates how the two can be used interchangeably to take advantage of the benefits of both technologies. For geometries that can be machined using a single setup orientation, CNC machining is often the fastest, most cost-effective method. For parts with complex geometries or parts which require a large proportion of the overall material volume to be machined away as scrap, AM can be used to more quickly and economically produce the part than when using CNC.

## 2.5 The Use of Layers

A key enabling principle of AM part manufacture is the use of layers as finite 2D cross-sections of the 3D model. Almost every AM technology builds parts using layers of material added together, primarily due to the simplification of building 3D objects. Using 2D representations to represent cross-sections of a more complex 3D feature has been common in many applications outside AM. The most obvious example of this is how cartographers use a line of constant height to represent hills and other geographical reliefs. These contour lines, or iso-heights, can be used as plates that can be stacked to form representations of geographical regions. The gaps between these 2D cross-sections cannot be precisely represented and are therefore approximated, or interpolated, in the form of continuity curves connecting these layers. Such techniques can also be used to provide a 3D representation of other physical properties, like isobars or isotherms on weather maps.

Architects have also used such methods to represent landscapes of actual or planned areas, like that used by an architect firm in Fig. 2.5 [11]. The concept is

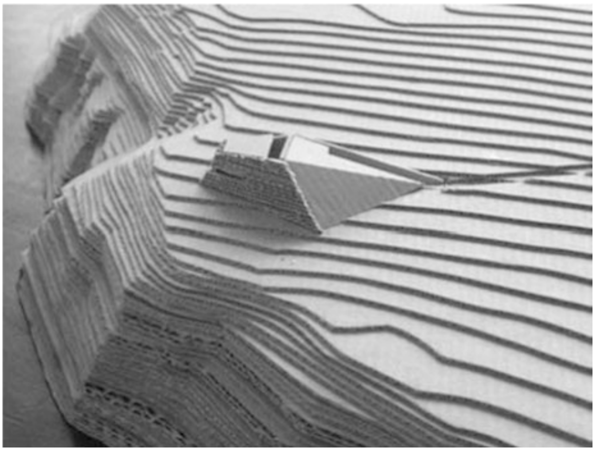

**Fig. 2.5** An architectural landscape model, illustrating the use of layers. (Photo courtesy of LiD)

particularly logical to manufacturers of buildings who also use an additive approach, albeit not using layers. Consider how the pyramids in Egypt and in South America were created. Notwithstanding how they were fabricated, it's clear that they were created using a layered approach, adding material as they went.

## 2.6 Classification of AM Processes

There are numerous ways to classify AM technologies. A popular approach is to classify according to baseline technology, like whether the process uses lasers, printer technology, extrusion technology, etc. [12, 13]. Another approach is to collect processes together according to the type of raw material input [14, 15]. The problem with these classification methods is that some processes get lumped together in what seems to be odd combinations (like Selective Laser Sintering being grouped together with 3D Printing) or that some processes that may appear to produce similar results end up being separated (like stereolithography and material jetting (MJT) with photopolymers). It is probably inappropriate, therefore, to use a single classification approach.

An early classification method was described by Pham [16], which uses a two-dimensional classification method as shown in Fig. 2.6. The first dimension relates to the method by which the layers are constructed. Earlier technologies used a single point source to draw across the surface of the base material. Later systems increased the number of sources to increase the throughput, which was made possible with the use of droplet deposition technology, for example, which can be constructed into a one-dimensional array of deposition heads. Further throughput improvements are possible with the use of 2D array technology using the likes of digital micromirror devices (DMDs) and high-resolution display technology, capable of exposing an entire surface in a single pass. However, just using this classifica-

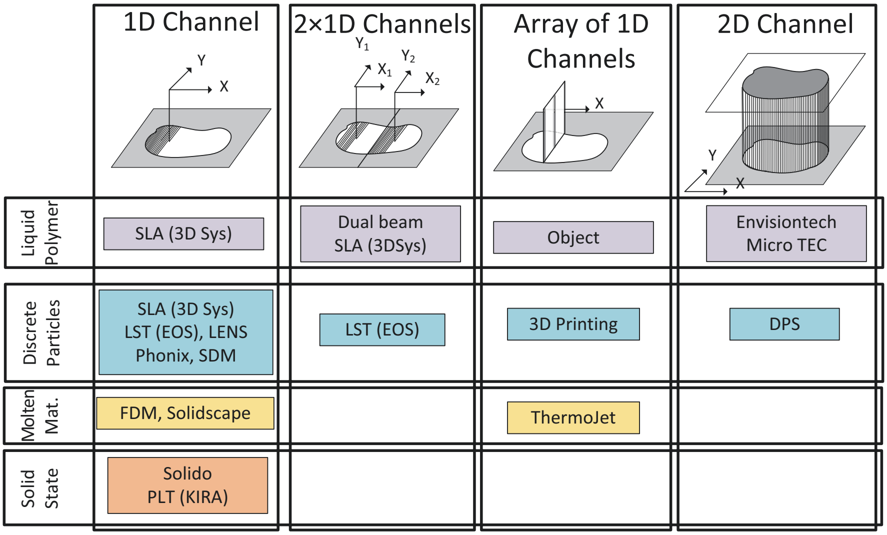


**Fig. 2.6** Layered manufacturing (LM) processes as classified by Pham (note that this diagram has been amended to include some recent AM technologies)

tion results in the previously mentioned anomalies where numerous dissimilar processes are grouped together. This is solved by introducing a second dimension of raw material to the classification. Pham uses four separate material classifications: liquid polymer, discrete particles, molten material, and laminated sheets. Some more exotic systems mentioned in this book may not fit directly into this classification. An example is the possible deposition of composite material, like concrete, using an extrusion-based technology. This fits well as a 1D channel, but the material is not explicitly listed as it is not really a molten material. Furthermore, future systems may be developed that use 3D holography to project and fabricate complete objects in a single pass. As with many classifications, there can sometimes be processes or systems that lie outside them. If there are sufficient systems to warrant an extension to this classification, then it should not be a problem.

It should be noted that, in particular, 1D and 2 × 1D channel systems combine both vector- and raster-based scanning methods. Often, the outline of a layer is traced first before being filled in with regular or irregular scanning patterns. The outline is generally referred to as vector scanned, while the fill pattern can often be generalized as a raster pattern. The array methods tend not to separate the outline and the fill.

Most AM technology started using a 1D channel approach, although one of the earliest and now obsolete technologies, Solid Ground Curing from Cubital, used liquid photopolymers and essentially (although perhaps arguably) a 2D channel method. As technology developed, so more of the boxes in the classification array began to be filled. The empty boxes in this array may serve as a guide to researchers and developers for further technological advances. Most of the 1D array methods use at least 2 × 1D lines. This is similar to conventional 2D printing where each line deposits a different material in different locations within a layer. The Connex process using the PolyJet technology from Stratasys is a good example of this where it is possible to create parts with different material properties in a single step using this approach. Color 3D Printing is possible using multiple 1D arrays with ink or separately colored material in each. Note however that the part coloration in the sheet laminating Mcor process [17] is separated from the layer formation process, which is why it is defined as a 1D channel approach.

### *2.6.1 Liquid Polymer Systems*

As can be seen from Fig. 2.6, liquid polymers appear to be a popular material. The first commercial system was the 3D Systems Stereolithography process based on liquid photopolymers. A large portion of systems in use today are, in fact, not just liquid polymer systems but more specifically liquid photopolymer systems. However, this classification should not be restricted to just photopolymers, since a number of experimental systems are using hydrogels that would also fit into this category. Furthermore, the Fab@Home system developed at Cornell University in the USA and the open-source RepRap systems originating from Bath University in the UK also use liquid polymers with curing techniques other than UV or other wavelength optical curing methods [18, 19].

Using this material and a 1D channel or 2 × 1D channel scanning method, a great option is to use a laser like in the stereolithography process. Droplet deposition of polymers using an array of 1D channels can simplify the curing process to a floodlight (for photopolymers) or similar method. This approach was commercialized by the Israeli company Objet (now part of Stratasys) who use printer technology to print fine droplets of photopolymer "ink" [20]. One unique feature of the Objet system is the ability to vary the material properties within a single part. Parts can, for example, have soft-feel, rubber-like features combined with more solid resins to achieve a result similar to an overmolding effect.

Controlling the area to be exposed using digital micromirror devices or other high-resolution display technology obviates the need for any scanning at all, thus increasing throughput and reducing the number of moving parts. DMDs are generally applied to micron-scale additive approaches, like those used by Microtec in Germany [21]. For normal-scale systems, EnvisionTEC uses high-resolution DMD displays to cure photopolymer resin in their low-cost AM machines. The 3D Systems V-Flash process is also a variation on this approach, exposing thin sheets of polymer spread onto a build surface.

### *2.6.2 Discrete Particle Systems*

Discrete particles are normally powders that are generally graded into a relatively uniform particle size and shape and narrow size distribution. The finer the particles, the better, but there will be problems if the dimensions get too small in terms of controlling the distribution and dispersion. Again, the conventional 1D channel approach is to use a laser, this time to produce thermal energy in a controlled manner and, therefore, raise the temperature sufficiently to melt the powder. Polymer powders must therefore exhibit thermoplastic behavior so that they can be melted and remelted to permit bonding of one layer to another. There are a wide variety of such systems that generally differ in terms of the material that can be processed. The two main polymer-based systems commercially available are the Selective Laser Sintering (SLS) technology marketed by 3D Systems [22] and the EOSINT processes developed by the German company EOS [23].

Application of printer technology to powder beds resulted in the (original) 3D Printing (3DP) process. This technique was developed by researchers at MIT in the USA [24]. Droplet printing technology is used to print a binder, or glue, onto a powder bed. The glue sticks the powder particles together to form a 3D structure. This basic technique has been developed for different applications dependent on the type of powder and binder combination. The most successful approaches use low-cost, starch-, and plaster-based powders with inexpensive glues, as commercialized by Z Corp, USA [25], which is now part of 3D Systems. Ceramic powders and appropriate binders were similarly used in the Direct Shell Production Casting (DSPC) process by Soligen [26] as part of a service to create shells for casting of metal parts. Alternatively, if the binder were to contain an amount of drug, 3DP can be used to create controlled delivery-rate drugs like in the process developed by the US company Therics. Neither of these last two processes has proven to be as successful as that licensed by Z Corp/3D Systems. One particular advantage of the Z Corp technology is that the binders can be jetted from multi-nozzle print heads. Binders coming from different nozzles can be different, and, therefore, subtle variations can be incorporated into the resulting part. The most obvious of these is the color that can be incorporated into parts.

### *2.6.3 Molten Material Systems*

Molten material systems are characterized by a preheating chamber that raises the material temperature to the melting point so that it can flow through a delivery system. The most well-known method for doing this is the Fused Deposition Modeling (FDM) Material Extrusion (MEX) technology developed by the US company Stratasys [27]. This approach extrudes the material through a nozzle in a controlled manner. Two extrusion heads are often used so that support structures can be fabricated from a different material to facilitate part cleanup and removal. It should be noted that there are now a huge number of variants of this technology due to the lapse of key FDM patents. This competition has driven the price of these machines down to such a level that individual buyers can afford to have their own machines at home.

Printer technology has also been adapted to suit this material delivery approach. One technique, developed initially as the Sanders prototyping machine, that later became Solidscape, USA [28], and which is now part of Stratasys, is a 1D channel system. A single jet piezoelectric deposition head lays down wax material. Another head lays down a second wax material with a lower melting temperature that is used for support structures. The droplets from these print heads are very small so the resulting parts are fine in detail. To further maintain the part precision, a planar cutting process is used to level each layer once the printing has been completed. Supports are removed by inserting the complete part into a temperature-controlled bath that melts the support material away, leaving the part material intact. The use of wax along with the precision of Solidscape machines makes this approach ideal for precision casting applications like jewelry, medical devices, and dental castings. Few machines are sold outside of these niche areas.

The 1D channel approach, however, is very slow in comparison with other methods, and applying a parallel element does significantly improve throughput. The Thermojet technology from 3D Systems also deposits a wax material through droplet-based printing heads. The use of parallel print heads as an array of 1D channels effectively multiplies the deposition rate. The Thermojet approach, however, is not widely used because wax materials are difficult and fragile when handled. Thermojet machines are no longer being made, although existing machines are commonly used for investment casting patterns.

### *2.6.4 Solid Sheet Systems*

One of the earliest AM technologies was the Laminated Object Manufacturing (LOM) system from Helisys, USA. This technology used a laser to cut out profiles from sheet paper, supplied from a continuous roll, which formed the layers of the final part. Layers were bonded together using a heat-activated resin that was coated on one surface of the paper. Once all the layers were bonded together, the result was very like a wooden block. A hatch pattern cut into the excess material allowed the user to separate away waste material and reveal the part.

A similar approach was used by the Japanese company Kira, in their Solid Center machine [29], and by the Israeli company Solidimension with their Solido machine. The major difference is that both these machines cut out the part profile using a blade similar to those found in vinyl sign-making machines, driven using a 2D plotter drive. The Kira machine used a heat-activated adhesive applied using laser printing technology to bond the paper layers together. Both the Solido and Kira machines have been discontinued for reasons including poor reliability, material wastage, and the need for excessive amounts of manual post-processing. Mcor Technologies expanded upon this approach and produces a modern version of this technology, using low-cost color printing to make it possible to make laminated color parts [17].

### 2.6.5 New AM Classification Schemes

In this book, we use a version of Pham's classification introduced in Fig. 2.6. Instead of using the 1D and 2 × 1D channel terminology, we will typically use the terminology "point" or "point-wise" systems. For arrays of 1D channels, such as when using inkjet print heads, we refer to this as "line" processing. 2D channel technologies will be referred to as "layer" processing. Last, although no current commercialized processes are capable of this, holographic-like techniques are considered "volume" processing.

The technology-specific descriptions starting in Chap. 4 are based, in part, upon a separation of technologies into groups where processes which use a common type of machine architecture and similar materials transformation physics are grouped together. This grouping is a refinement of an approach introduced by Stucker and Janaki Ram in the CRC Materials Processing Handbook [30]. In this grouping scheme, for example, processes which use a common machine architecture developed for stacking layers of powdered material and a materials transformation mechanism using heat to fuse those powders together are all discussed in the PBF chapter. These are grouped together even though these processes encompass polymer, metal, ceramic, and composite materials, multiple types of energy sources (e.g., lasers and infrared heaters), and point-wise and layer processing approaches. Using this classification scheme, all AM processes fall into one of seven categories. An understanding of these seven categories should enable a person familiar with the concepts introduced in this book to quickly grasp and understand an unfamiliar AM process by comparing its similarities, benefits, drawbacks, and processing characteristics to the other processes in the grouping into which it falls.

This classification scheme from the first edition of this textbook had an important impact on the development and adoption of ASTM/ISO standard terminology. The authors were involved in these consensus standards activities, and we have agreed to adopt the modified terminology from ASTM F42 and ISO TC 261 in the second and subsequent editions [31]. Of course, in the future, we will continue to support the ASTM/ISO standardization efforts and keep the textbook up to date.

The seven process categories are presented here. Chapters 4, 5, 6, 7, 8, 9, and 10 cover each one in detail:

- Vat Photopolymerization (VPP): processes that utilize a liquid photopolymer that is contained in a vat and processed by selectively delivering energy to cure specific regions of a part cross-section.
- Powder Bed Fusion (PBF): processes that utilize a container filled with powder that is processed selectively using an energy source, most commonly a scanning laser or electron beam.
- Material Extrusion (MEX): processes that deposit a material by extruding it through a nozzle, typically while scanning the nozzle in a pattern that produces a part cross-section.
- Material Jetting (MJT): processes that selectively deposit droplets of feedstock material.

- Binder Jetting (BJT): processes where a liquid bonding agent is printed into a powder bed in order to form part cross-sections.
- Sheet Lamination (SHL): processes that bond sheets of material to form a part.
- Directed Energy Deposition (DED): processes that simultaneously deposit a material (usually powder or wire) and provide energy to process that material through a single deposition device.

## 2.7 Heat Sources

### *2.7.1 Lasers*

Many of the earliest AM systems were based on laser technology. The reasons are that lasers provide a high intensity and highly collimated beam of energy that can be moved very quickly in a controlled manner with the use of directional mirrors. Since AM requires the material in each layer to be solidified or joined in a selective manner, lasers are ideal candidates for use, provided the laser energy is compatible with the material transformation mechanisms. There are two kinds of laser processing used in AM: curing and heating. With photopolymer resins the requirement is for laser energy of a specific frequency that will cause the liquid resin to solidify or "cure." Usually this laser is in the ultraviolet range, but other frequencies can be used. For heating, the requirement is for the laser to carry sufficient thermal energy to cut through a layer of solid material, to cause powder to melt, or to cause sheets of material to fuse. For powder processes, for example, the key is to melt the material in a controlled fashion without creating too great a buildup of heat, so that when the laser energy is removed, the molten material rapidly solidifies again. For cutting, the intention is to separate a region of material from another in the form of laser cutting. Earlier AM machines used tube lasers to provide the required energy, but most manufacturers have switched to solid-state technology, which provides greater efficiency, lifetime, and reliability.

A laser generally has the following components: (I) gain medium, (II) a pumping energy source, and (III) optical resonator. The gain medium is located in the optical resonator and amplifies the light beam by stimulating emission. Lasers are classified according to the type of gain medium. Figure 2.7 shows the classification of lasers.

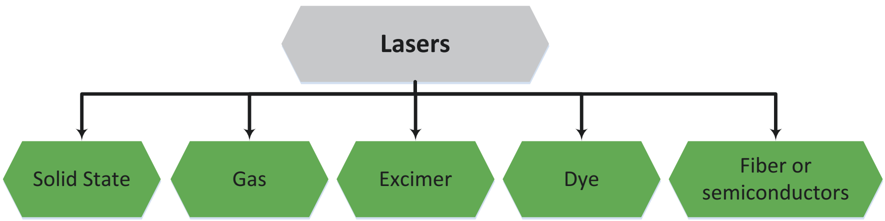


**Fig. 2.7** Different lasers

In Additive Manufacturing gas, solid-state and fiber lasers are the most commonly used.

Early AM machines used gas lasers, primarily $CO_2$. The most common gas lasers produce infrared output wavelengths ranging from 9000 to 11,000 nm with an efficiency of 5–20% and power ranging from 100 to 20,000 W. The simplicity of a gas laser system brings low cost, highly reliability, and system compactness, which are the main reasons that $CO_2$ lasers are the workhorse of precision manufacturing. However, their output power is relatively non-stable because of thermal expansion and contraction of the laser structure due to the heat generated in the process of energy pumping to a large volume of $CO_2$ gas. Low light absorption in the infrared region is another problem of $CO_2$ lasers, with high reflectivity among metals in particular.

Nd:YAG is a solid-state laser, and the gain medium is made of rod-shaped Nd:YAG crystals. The gain medium is pumped by a flash lamp or 808 nm laser diode to produce a near-infrared output wavelength of 1064 nm. The significant advantages of this laser over $CO_2$ are system compactness and efficiency in delivering the beam through optical fibers. This laser can be operated both in continuous mode using crystals doped with low concentrations and in pulsed mode using highly doped crystals. The maximum output power for continuous and pulse lasers is a few kW and 20 kW, respectively. This laser suffers from relatively low electrical-to-optical power conversion efficiency which leads to lower beam quality. The reason is most of the unabsorbed energy is dissipated as heat. This heat leads to thermal lensing and poor beam quality. Diode-pumped solid-state (DPSS) lasers are a solution for these problems.

The gain medium for fiber lasers is made from rare earth-doped optical fibers such as Yb-fibers. This fiber has high quantum efficiency (−95%). They can produce a near-infrared laser beam in the range 1030–1070 nm output wavelength and have high electrical-to-optical efficiency (−25%), excellent beam quality, robustness against environmental disturbances, and system compactness. Light propagation inside the fiber, unexpected polarization change from fiber bending, vibration, and temperature variation are typical problems of Yb-fiber lasers.

Excited dimer (Excimers) are gas mixtures containing a noble gas (e.g., argon, krypton, or xenon), a halogen (e.g., fluorine or chlorine), and a buffer gas (typically neon or helium). If the gain medium is made by excimers, the system is called an excimer laser. In this laser nanosecond pulses in the ultraviolet region are produced by pumping excimers using pulsed electrical discharge. The wavelength of excimers is in the range of 157–351 nm, and average output power can go up to a few hundreds of Watts. Most materials have a high absorptivity in the UV region, which is a significant advantage. Disadvantages of this laser are poor beam quality, high maintenance, and high running cost.

### 2.7.2 Electron Beam

An electron beam is another energy source used to melt materials in Additive Manufacturing. In this method free electrons in a vacuum can be controlled and positioned by electric and magnetic fields to shape a beam. When a high-velocity beam of electrons contacts solid matter, the kinetic energy is transformed to heat. This high heat, when concentrated, is an efficient means for melting materials that are electrically conductive. Electron beams require a vacuum chamber, since electrons scatter and diffuse if they interact with gas atoms between the electron gun and the material being heated. Electron beam melting (EBM) has a higher production rate compared to laser beam melting due to a higher energy density. A greater energy density leads to Marangoni convection in the melting area, which results in lower surface quality (roughness) and thus higher dimensional deviations. More Additive Manufacturing machines are equipped with lasers than electron beams.

### 2.7.3 Electric Arc/Plasma Arc

The electrical breakdown of a gas in a nonconductive medium like air produces plasma and an electric arc, plasma arc, or arc discharge. A normal gas molecule at room temperature consists of two or more atoms. When the temperature of the molecule increases to 2000 °C, atoms are separated. If the gas temperature goes up to 3000 °C, some of the atoms are separated, and gas is ionized and decomposition of atoms happens. This gas is called plasma and is a conductor of electricity, and so plasma is the fourth state of matter.

The plasma is accompanied by electrical discharge. The source of heat production in plasma is the recombination of electrons and ions to form atoms and the recombining of atoms to form molecules. This released bonding energy increases the kinetic energy of atoms or molecules formed by recombination and can be used in different material processing. This temperature can go up to 30,000 °C and be used for melting and evaporation of almost all materials.

Electrical and plasma arcs are used in Additive Manufacturing mainly in Directed Energy Deposition (DED) using wire. This is also referred to as Wire Arc Additive Manufacturing (WAAM). In WAAM motion can be provided either by robotic systems or Computer Numerical Controlled gantries. In this method wire plays the role of a consumable electrode [32].

Electrical or plasma arcs are used particularly for building large components due to their high deposition rate, low material and equipment costs, and good structural integrity. These specifications characterize it as a suitable candidate for replacing the conventional methods of manufacturing from solid billets or large forgings, notably with regard to low and medium complexity parts.

## 2.8 Metal Systems

One of the most important historical developments in AM was the proliferation of direct metal processes. Machines like the EOSINT-M [21] and Laser Engineered Net Shaping (LENS) have been around for a number of years [33, 34]. Recent additions from other companies and improvements in laser technology, machine accuracy, speed, and cost have opened up this market, and today, metal AM is a major driver of AM adoption.

Most direct metal systems work using a point-wise method, and nearly all of them utilize metal powders as input. The main exception to this approach is the Sheet Lamination (SHL) processes, particularly the Ultrasonic Consolidation process commercialized by Solidica, USA (now Fabrisonic), which uses sheet metal laminates that are ultrasonically welded together [35]. Of the powder systems, almost every newer machine uses a powder spreading approach similar to the Selective Laser Sintering process, followed by melting using an energy beam. This energy is normally a high-power laser, except in the case of the EBM process by the Swedish company Arcam [36] (now part of GE). Another approach is the LENS powder delivery system used by Optomec [31]. This machine employs powder delivery through a nozzle placed above the part. The powder is melted where the material converges with the laser and the substrate. This approach allows the process to be used to add material to an existing part, which means it can be used for repair of expensive metal components that may have been damaged, like chipped turbine blades and injection mold tool inserts.

## 2.9 Hybrid Systems

Some of the machines described above are, in fact, hybrid additive/subtractive processes rather than purely additive. Including a subtractive component can assist in making the process more precise. An example is the use of planar milling at the end of each additive layer in the Sanders and Objet machines. This stage makes for a smooth planar surface onto which the next layer can be added, negating cumulative effects from errors in droplet deposition height.

It should be noted that when subtractive methods are used, waste will be generated. Machining processes require removal of material that in general cannot easily be recycled. Similarly, many additive processes require the use of support structures, and these too must be removed or "subtracted."

It can be said that with the Objet process, for instance, the additive element is dominant and that the subtractive component is important but relatively insignificant. There have been a number of attempts to merge subtractive and additive technologies together where the subtractive component is the dominant element. An excellent example of this is the Stratoconception approach [37], where the original CAD models are divided into thick machinable layers. Once these layers are machined, they are bonded together to form the complete solid part. This approach works very well for very large parts that may have features that would be difficult to machine using a multi-axis machining center due to the accessibility of the tool. This approach can be applied to foam- and wood-based materials or to metals. For structural components it is important to consider the bonding methods. For high-strength metal parts, diffusion bonding may be an alternative.

A lower-cost solution that works in a similar way is Subtractive RP (SRP) from Roland [38], who is also famous for plotter technology. SRP makes use of Roland desktop milling machines to machine sheets of material that can be sandwiched together, similar to Stratoconception. The key is to use the exterior material as a frame that can be used to register each slice to others and to hold the part in place. With this method not all the material is machined away, and a web of connecting spars are used to maintain this registration.

Another variation of this method that was never commercialized was Shape Deposition Manufacturing (SDM), developed mainly at Stanford and Carnegie-Mellon Universities in the USA [39]. With SDM, the geometry of the part is devolved into a sequence of easier to manufacture parts that can in some way be combined together. A decision is made concerning whether each subpart should be manufactured using additive or subtractive technology dependent on such factors as the accuracy, material, geometrical features, functional requirements, etc. Furthermore, parts can be made from multiple materials, combined together using a variety of processes, including the use of plastics, metals, and even ceramics. Some of the materials can also be used in a sacrificial way to create cavities and clearances. Additionally, the "layers" are not necessarily planar, nor constant in thickness. Such a system would be unwieldy and difficult to realize commercially, but the ideas generated during this research have influenced many studies and systems thereafter.

In this book, for technologies where both additive and subtractive approaches are used, these technologies are discussed in the chapter where their additive approach best fits.

## 2.10 Milestones in AM Development

We can look at the historical development of AM in a variety ways. The origins may be difficult to properly define, and there was certainly a lot of activity in the 1950s and 1960s related to joining materials together to form objects. But development of the associated technologies (computers, lasers, controllers, etc.) caught up with the concept in the early 1980s. Interestingly, parallel patents were filed in 1984 in Japan (Murutani), France (Andre et al.) and in the USA (Masters in July and Hull in August). All of these patents described a similar concept of fabricating a 3D object by selectively adding material layer-by-layer. While earlier work in Japan is quite well-documented, proving that this concept could be realized, it was the patent by Charles Hull that is generally recognized as the most influential since it gave rise to

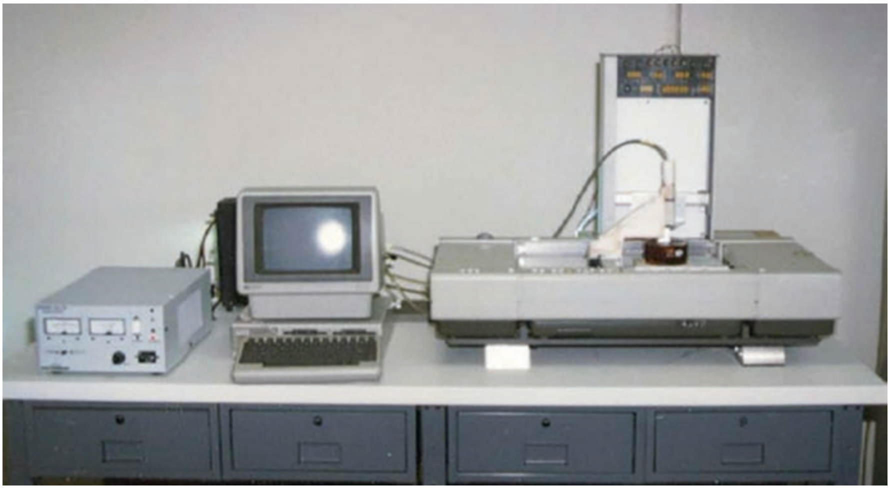

**Fig. 2.8** The first AM technology from Hull, who founded 3D Systems (photo courtesy of 3D Systems)

3D Systems. This was the first company to commercialize AM technology with the Stereolithography apparatus (Fig. 2.8).

Further patents came along in 1986, resulting in three more companies, Helisys (Laminated Object Manufacturing or LOM), Cubital (with Solid Ground Curing, SGC), and DTM with their Selective Laser Sintering (SLS) process. It is interesting to note neither Helisys nor Cubital exist anymore, and only SLS remains as a commercial process with DTM merging with 3D Systems in 2001. In 1989, Scott Crump patented the Fused Deposition Modeling (FDM) process, forming the Stratasys Company. Also in 1989 a group from MIT patented the 3D Printing (3DP) process. These processes from 1989 are heavily used today, with FDM variants currently being the most successful. Rather than forming a company, the MIT group licensed the 3DP technology to a number of different companies, who applied it in different ways to form the basis for different applications of their AM technology. The most successful of these were Z Corp, which focused mainly on low-cost technology, and ExOne, which focused on powdered metal and sandcasting applications.

Inkjet technology has become employed to deposit droplets of material directly onto a substrate, where that material hardens and becomes the part itself rather than just as a binder. Sanders developed this process in 1994, and Objet also used this technique to print photocurable resins in droplet form in 2001.

There have been numerous failures and successes in AM history, with the previous paragraphs mentioning only a small number. However, it is hard to know whether a specific technology may have failed because of poor business models or by poor timing rather than having a poor process. Helisys appears to have failed with their LOM machine, but there have been at least five variants from Singapore, China, Japan, Israel, and Ireland. The most recent Mcor process laminates colored sheets together rather than the monochrome paper sheets used in the original LOM machine. However, Mcor went into receivership, and their IP was acquired by CleanGreen3D in late 2019. Perhaps this is a better application, and perhaps the technology is in a better position to become successful in the future; however the business track record for LOM-based businesses has been consistently poor. Another example is the defunct Ballistic Particle Manufacturing process, which used a 5-axis mechanism to direct wax droplets onto a substrate. Although no company currently uses such an approach for polymers, similar 5-axis deposition schemes are being used for depositing metal and composites.

Another important trend that is impacting the development of AM technology is the expiration of many of the foundational patents for key AM processes. We saw an explosion of MEX vendors systems and systems after the first FDM patents expired in the early 2010s. Initial patents in the stereolithography, laser sintering, and LOM have also expired, which is leading to a proliferation of technologies, processes, machines, companies, and competition worldwide.

## 2.11 AM around the World

As was mentioned, early patents were filed in Europe (France), the USA, and Asia (Japan) almost simultaneously. In early years, most pioneering and commercially successful systems came out of the USA. Companies like Stratasys, 3D Systems, and Z Corp have spearheaded the way forward. These companies have generally strengthened over the years, but most new companies have come from outside the USA.

In Europe, the first company with a worldwide impact in AM was EOS, Germany. EOS stopped making SL machines following settlement of disputes with 3D Systems but continues to make PBF systems which use lasers to melt polymers, binder-coated sand, and metals. Companies from elsewhere in Europe are smaller but are competitive in their respective marketplaces. Examples of these companies include Phenix [40] (now part of 3D Systems), Arcam, Strataconception, SLM Solutions, Trumpf, Additive Industries, and Materialise. The last of these, Materialise from Belgium [41], has seen considerable success in developing software tools to support AM technology.

In the early 1980s and 1990s, a number of Japanese companies focused on AM technology. Large companies like Sony and Kira, who established subsidiaries to build AM technology, also became involved. Much of the Japanese technology was based around the photopolymer curing processes. With 3D Systems dominant in much of the rest of the world, these Japanese companies struggled to find market, and many of them failed to become commercially viable, even though their technology showed some initial promise. Some of this demise may have resulted in the unusually slow uptake of CAD technology within Japanese industry in general. Although the Japanese company CMET [42] still seems to be doing well, you will likely find more non-Japanese made machines in Japan than home-grown ones.

AM technology has also been developed in other parts of Asia, most notably in Korea and China. Korean AM companies have had little international impact; however, quite a few Chinese manufacturers have been active for a number of years and are beginning to make inroads into markets in Europe and the Americas. Patent conflicts with the earlier US, Japanese, and European designs have meant that many of these machines were not able to be sold outside of China. Earlier Chinese machines were also thought to be of questionable quality, but more recent machines have markedly improved performance (like the machine shown in Fig. 2.9). Chinese machines primarily reflect the SL, FDM, and SLS technologies found elsewhere in the world, and the expiration of initial patents for almost every type of AM technology has created an opening for Chinese companies to compete worldwide.

A particular country of interest in terms of AM technology development is Israel. One of the earliest AM machines was developed by the Israeli company Cubital. Although this technology was not a commercial success, in spite of early installations around the world, they demonstrated a number of innovations not found in other machines, including layer processing through a mask, removable secondary support materials and milling after each layer to maintain a constant layer thickness. Some of the concepts used in Cubital can be found in Sanders machines as well as machines from another Israeli company, Objet. Objet joined with Stratasys and moved Stratasy's headquarters to Israel. The success of Objet's droplet deposition technology as well as other software and hardware startups in the AM arena makes Israel an outsized player in AM relative to its size.

**Fig. 2.9** AM technology from Beijing Yinhua Co. Ltd., China

## 2.12 AM Standards

Standards in conventional manufacturing play significant roles in helping organizations develop, manufacture, and supply goods and services in a more efficient, effective, and safer manner. Standards in AM can fulfill the same roles. Companies use AM standards to learn to adopt AM technologies, gain confidence in AM usage, communicate with suppliers and customers using a common language, and specify materials and their properties, among others. More specifically, current AM standards assist the specification of types of technical requirements expected when ordering parts, specification of what is needed to qualify a material or process, understanding of how to ensure safe machine operations and environments, and characterization of properties of fabricated parts.

In 2009, the authors of this book worked with ASTM International to create the F42 Committee to develop AM standards. Several other standards organizations followed in the next years, including ISO, SAE, and ASME. In 2013, ASTM and ISO formed a partnership to develop and promote AM standards in a landmark agreement between the organizations. The Society of Automotive Engineers (SAE) is developing standards for the aerospace industry for metal AM technologies. The American Society of Mechanical Engineers (ASME) is investigating modifications to their dimensioning and tolerancing standards to accommodate unique characteristics of AM. In 2017, a partnership between the American National Standards Institute (ANSI) and America Makes [43] released a standardization roadmap that identified 89 gaps, i.e., topics for which standards are needed, and corresponding recommendations [44]; their second roadmap in 2018 continues to guide standardization efforts worldwide.

Within ASTM F42, standards development occurs within six subcommittees on test methods, design, materials and processes, environment health and safety, applications (which has nine sub-subcommittees for various industries), and data. The test methods subcommittee develops new test standards for AM-fabricated specimens and provides guides on how to adopt existing standards to the unique characteristics of AM parts. The design subcommittee develops data exchange standards, including the Additive Manufacturing Format (AMF) [45]; guides on how to use data exchange formats for multiple materials, medical imaging, etc.; and design for AM guides. In the materials and processes subcommittee, standards are developed for AM-fabricated materials, technical guides for specific processes, finished part properties, post-processing methods, and requirements for purchased AM parts. The last topic is represented by a joint ISO/ASTM standard [46] that specifies the types of information that suppliers and customers of AM parts should consider to meet acceptance requirements. The environment, health, and safety subcommittee develops standards for operator safety, allowable indoor air quality requirements for AM printers, and related topics. In the applications subcommittee, many standards under development focus on qualification issues that arise in a wide range of industries. Additionally, they have participation from other US federal agencies that oversee specific industries, including the US Food and Drug Administration (FDA) for

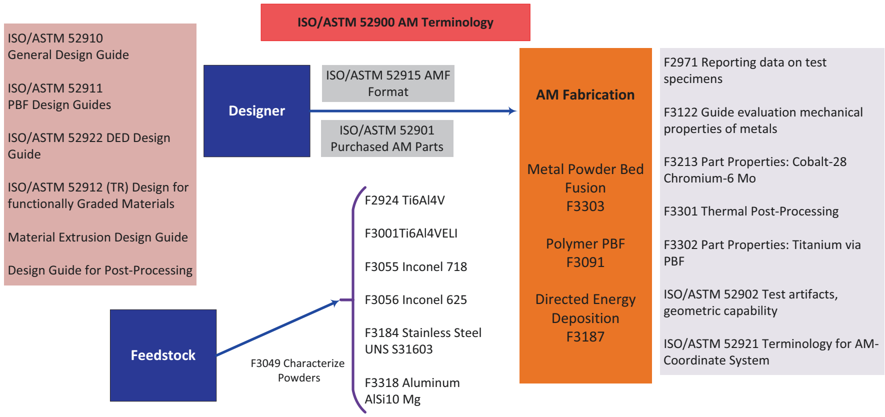


**Fig. 2.10** Current ASTM and ISO standards and their relationships

medical devices and the Federal Aviation Administration (FAA) for aerospace applications.

A snapshot of ASTM and ISO standards available in 2020 is shown in Fig. 2.10, arranged according to the product development stage of relevance. The AM terminology standard provides the foundation for the others. The designer receives guidance from the various design guides during the design process and then can rely on the AMF file format to exchange their parts with the manufacturer. For contracting, the purchased AM parts standard provides guidance. Many standards for materials have been developed, with a focus on metals so far, as well as a standard on powder characterization. For AM fabrication, standards support test specimen reporting data, guidance on evaluating mechanical properties, finished part properties, post-processing methods, etc.

As mentioned, several organizations are actively developing standards that should impact AM technology and practices. The specifics presented about ASTM and ISO are meant to illustrate some of the current accomplishments and organization of the activity. In the future, a much more comprehensive set of standards will be available to guide the AM field; these standards will be the product of concerted efforts among many professionals in many standards organizations, companies, universities, and government agencies.

## 2.13 The Future? Rapid Prototyping Develops into Direct Digital Manufacturing

How might the future of AM look? The ability to "grow" parts may form the core to the answer to that question. The true benefit behind AM is the fact that we do not really need to design the part according to how it is to be manufactured. We would prefer to design the part to perform a particular function. Avoiding the need to consider how the part can be manufactured certainly simplifies the process of design and allows the designer to focus more on the intended application. The design flexibility of AM is making this more and more possible.

An example of geometric flexibility is customization of a product. If a product is specifically designed to suit the needs of a unique individual, then it can truly be said to be customized. Imagine being able to modify your mobile phone so that it fits snugly into your hand based on the dimensions gathered directly from your hand. Imagine a hearing aid that can fit precisely inside your ear because it was made from an impression of your ear canal (like those shown in Fig. 2.11). Such things are possible using AM because it has the capacity to make one-off parts, directly from digital models that may not only include geometric features but may also include biometric data gathered from a specific individual.

With improvements in AM technology, the speed, quality, accuracy, and material properties have all developed to the extent that parts can be made for final use and not just for prototyping. The terms Rapid Manufacturing and Direct Digital Manufacturing (RM and DDM) gained popularity prior to the adoption of the term Additive Manufacturing to represent the use of AM to produce parts which will be used as an end product. Certainly we will continue to use this technology for prototyping for years to come, but we are already entering a time when it is commonplace to manufacture products in low volumes or unique products using AM. We even see these machines being used as home fabrication devices for hobbyists.

## 2.14 Questions

1. (a) Based upon an Internet search, describe the Solid Ground Curing process developed by Cubital. (b) Solid Ground Curing has been described as a 2D channel (layer) technique. Could it also be described in another category? Why?
2. Make a list of five different metal AM technologies that are currently available on the market today. How can you distinguish between the different systems? What different materials can be processed in these machines?
3. NC machining is often referred to as a 2.5D process. What does this mean? Why might it not be regarded as fully 3D?

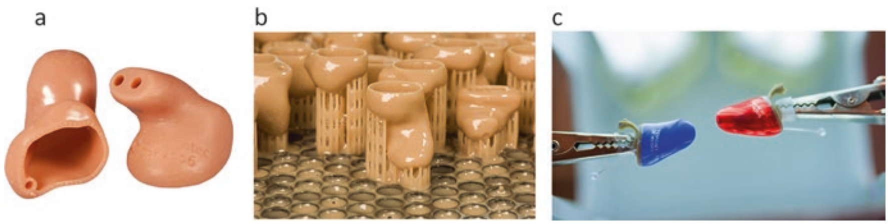


**Fig. 2.11** RM of custom hearing aids, from a wax ear impression, on to the machine to the final product. (Photo courtesy of EnvisionTEC and Sonova) [47, 48]

4. Provide three instances where a layer-based approach has been used in fabrication, other than AM.
5. Find five countries not specifically mentioned in this chapter where AM technology has been developed commercially and describe the machines.
6. Home fabrication using AM was an area of extensive market speculation in the late 2010s. But adoption of AM as a home fabrication method remains very low as of 2020. Why do you think this is? Do you see a large future opportunity for home fabrication, or do you think it will stay a niche, hobbyist market? Why or why not?
7. How might the future of Additive Manufacturing (AM) look? Give one specific example of geometric flexibility as a customization of a product.
8. Which of the Additive Manufacturing processes do you believe to be most suitable for home/domestic use and why?
9. What are four ways AM relies on computers that are different from traditional manufacturing?
10. Briefly describe some of the technologies that have contributed to the advancement of AM techniques.
11. MIT performed a study on using silkworm patterns for distributing silk in 2013 (available http://www.dezeen.com/2013/03/13/mit-researchers-to-3d-print-a-pavilion-by-imitating-silkworms/). How does this apply to Additive Manufacturing?
12. Find three parts that were created via three differing Additive Manufacturing Technologies. Present the picture of the part, the process used for production, the material used, and what is it about the part that gives an idea of the process used to create it.
13. Describe three Additive Manufacturing process types and attributes. Include example companies, materials utilized in machines, and typical markets.
14. What is the AMF format? What are the differences between the AMF format and an STL file? Compare the AMF format to STL files by describing at least 5 advantages AMF over STL file.

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