MODULE 1

Introduction and basic principles: Need for Additive Manufacturing, Generic AM process, Stereolithography or 3d printing, rapid proto typing, the benefits of AM, distinction between AM and CNC machining, other related technologies- reverse engineering technology.

Development of Additive Manufacturing Technology: Introduction, computers, computer-aided sign technology, other associated technologies, the use of layers, classification of AM processes, metal systems, hybrid systems, milestones in AM development.

Additive Manufacturing Process chain: Introduction, the eight steps in additive manufacture, variations from one AM machine to another, metal systems, maintenance of equipment, materials handling issues, design for AM, and application areas.

INTRODUCTION AND BASIC PRINCIPLES

NEED FOR ADDITIVE MANUFACTURING

The term Rapid Prototyping (or RP) is used in a variety of industries to describe a process for rapidly creating a system or part representation before final release or commercialization. In other words, the emphasis is on creating something quickly and that the output is a prototype or basis model from which further models and eventually the final product will be derived. Management consultants and software engineers both use the term Rapid Prototyping to describe a process of developing business and software solutions in a piecewise fashion that allows clients to test ideas and provide feedback during the development process. In a product development context, the term rapid prototyping was used widely to describe technologies which created physical prototypes directly from digital data. This text is about these technologies, first developed for prototyping, but now used for many more purposes.

Users of RP technology have come to realize that this term is inadequate and does not effectively describe more recent applications of the technology. Improvements in the quality of the output from these machines have meant that there is a much closer link to the final product. Many parts are in fact now directly manufactured in these machines; so it is not possible for us to label them as “prototypes.”

The term Rapid Prototyping also overlooks the basic principle of these technologies in that they all fabricate parts using an additive approach. A recently formed Technical Committee within ASTM International agreed that new terminology should be adopted. While this is still under debate, recently adopted ASTM consensus standards now use the term Additive Manufacturing.

Referred to in short as AM, the basic principle of this technology is that a model, initially generated using a three-dimensional Computer Aided Design (3D CAD) system, can be fabricated directly without the need for process planning. Although this is not in reality as simple as it first sounds, AM technology certainly significantly simplifies the process of producing complex 3D objects directly from CAD data. Other manufacturing processes require a careful and detailed analysis of the part geometry to determine things like the order in which different features can be fabricated, what tools and processes must be used, and what additional fixtures may be required to complete the part. In contrast, AM needs only some basic dimensional details and a small amount of understanding as to how the AM machine works and the materials that are used.

The key to how AM works is that parts are made by adding material in layers; each layer is a thin cross-section of the part derived from the original CAD data. Obviously in the physical world, each layer must have a finite thickness to it and so the resulting part will be an approximation of the original data, as illustrated by Fig. 1. The thinner each layer is, the closer the final part will be to the original. All commercialized AM machines to date use a layer-based approach; and the major ways that they differ are in the materials that can be used, how the layers are created, and how the layers are bonded to each other. Such differences will determine factors like the accuracy of the final part plus its material properties and mechanical properties. They will also determine factors like how quickly the part can be made, how much postprocessing is required, the size of the AM machine used, and the overall cost of the machine and process.

This chapter will introduce the basic concepts of Additive Manufacturing and describe a generic AM process from design to application. It will go on to discuss the implications of AM on design and manufacturing and attempt to help in understanding how it has changed the entire product development process. Since AM is an increasingly important tool for product development, the chapter ends with a discussion of some related tools in the product development process.

Fig. 1 CAD image of a teacup with further images showing the effects of building using different layer thicknesses

GENERIC AM PROCESS

AM involves a number of steps that move from the virtual CAD description to the physical resultant part. Different products will involve AM in different ways and to different degrees. Small, relatively simple products may only make use of AM for visualization models, while larger, more complex products with greater engineering content may involve AM during numerous stages and iterations throughout the development process. Furthermore, early stages of the product development process may only require rough parts, with AM being used because of the speed at which they can be fabricated. At later stages of the process, parts may require careful cleaning and postprocessing (including sanding, surface preparation and painting) before they are used, with AM being useful here because of the complexity of form that can be created without having to consider tooling. Later on, we will investigate thoroughly the different stages of the AM process, but to summarize, most AM processes involve, to some degree at least, the following eight steps (as illustrated in Fig. 2).

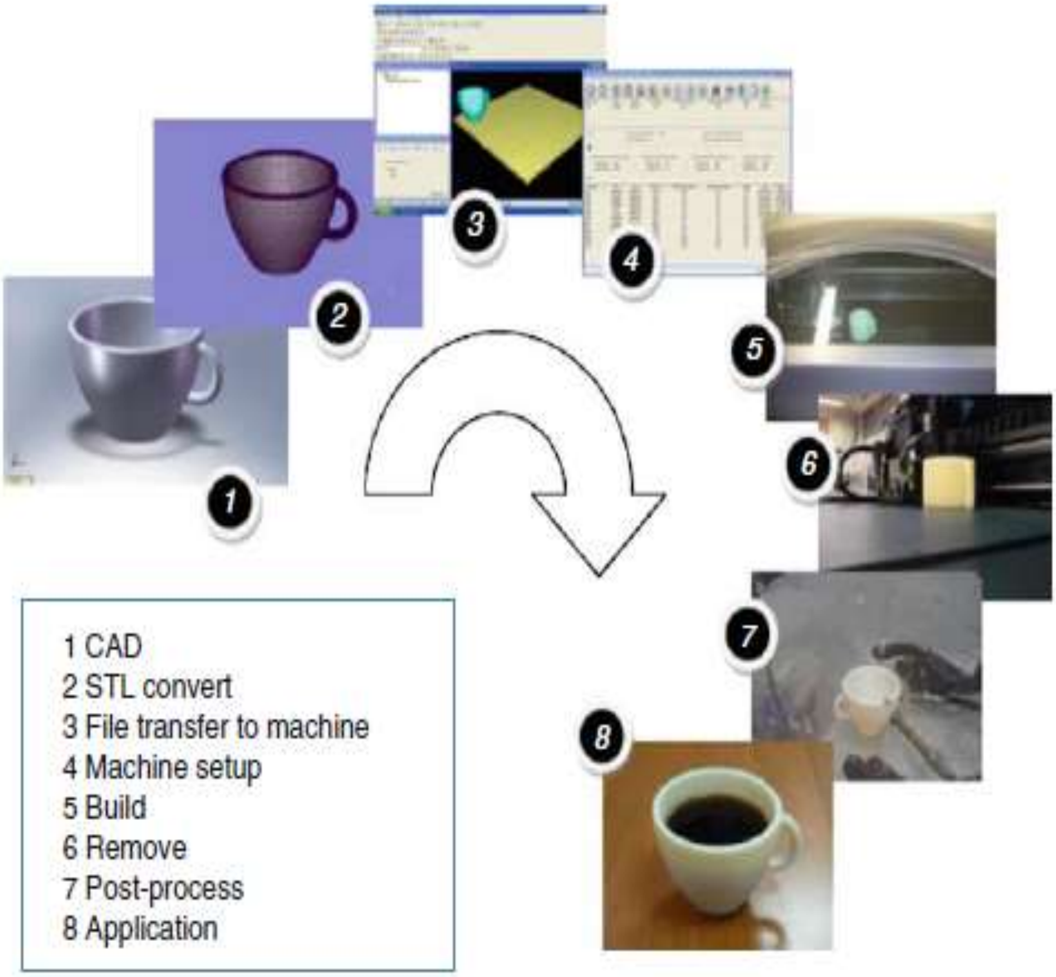

Fig. 2 Generic process of CAD to part, showing all 8 stages

Step 1: CAD

All AM parts must start from a software model that fully describes the external geometry. This can involve the use of almost any professional CAD solid modeling software, but the output must be a 3D solid or surface representation. Reverse engineering equipment (e.g., laser scanning) can also be used to create this representation.

Step 2: Conversion to STL

Nearly every AM machine accepts the STL file format, which has become a de facto standard, and nearly every CAD system can output such a file format. This file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.

Step 3: Transfer to AM Machine and STL File Manipulation

The STL file describing the part must be transferred to the AM machine. Here, there may be some general manipulation of the file so that it is the correct size, position, and orientation for building.

Step 4: Machine Setup

The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc.

Step 5: Build

Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.

Step 6: Removal

Once the AM machine has completed the build, the parts must be removed. This may require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts.

Step 7: Postprocessing

Once removed from the machine, parts may require an amount of additional cleaning up before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation.

Step 8: Application

Parts may now be ready to be used. However, they may also require additional treatment before they are acceptable for use. For example, they may require priming and painting to give an acceptable surface texture and finish. Treatments may be laborious and lengthy if the finishing requirements are very demanding.

STEREOLITHOGRAPHY OR 3D PRINTING

These two terms were initially used to describe specific machines. Stereolithography (SL) was termed by the US company 3D Systems and 3D Printing (3DP) was widely used by researchers at MIT who invented an ink-jet printing-based technology. Both terms allude to the use of 2D processes (lithography and printing) and extending them into the third dimension. Since most people are very familiar with printing technology, the idea of printing a physical three-dimensional object should make sense. Many consider that eventually the term 3D Printing will become the most commonly used wording to describe AM technologies.

RAPID PROTOTYPING

Rapid Prototyping was termed because of the process this technology was designed to enhance or replace. Manufacturers and product developers used to find prototyping a complex, tedious, and expensive process that often impeded the developmental and creative phases during the introduction of a new product. RP was found to significantly speed up this process and thus the term was adopted. However, users and developers of this technology now realize that AM technology can be used for much more than just prototyping.

Significant improvements in accuracy and material properties have seen this technology catapulted into testing, tooling, manufacturing, and other realms that are outside the "prototyping" definition. However, it can also be seen that most of the other terms described above are also flawed in some way. One possibility is that many will continue to use the term RP without specifically restricting it to the manufacture of prototypes, much in the way that IBM makes things other than business machines and that 3M manufactures products outside of the mining industry. It will be interesting to watch how terminology develops in the future.

Where possible, we have used the term Additive Manufacturing throughout this book as the generic word for the suite of technologies covered by this book. It should be noted that, in the literature, most of the terms introduced above are interchangeable; but different terminology may emphasize the approach used in a particular instance. Thus, both in this book and while reading other literature, the reader must consider the context to best understand what each of these terms means.

THE BENEFITS OF AM

Many people have described this technology as revolutionizing product development and manufacturing. Some have even gone on to say that manufacturing, as we know it today, may not exist if we follow AM to its ultimate conclusion. We might, therefore, like to ask "why is this the case?" What is it about AM that enthuses and inspires some to make these kinds of statements?

First, let's consider the "rapid" character of this technology. The speed advantage is not just in terms of the time it takes to build parts. The speeding up of the whole product development process relies much on the fact that we are using computers throughout. Since 3D CAD is being used as the starting point and the transfer to AM is relatively seamless, there is much less concern over data conversion or interpretation of the design intent. Just as 3D CAD is becoming What You

See Is What You Get (WYSIWYG), so it is the same with AM and we might just as easily say that What you See Is What You Build (WYSIWYB). The seamlessness can also be seen in terms of the reduction in process steps. Regardless of the complexity of parts to be built, building within an AM machine is generally performed in a single step. Most other manufacturing processes would require multiple and iterative stages to be carried out. As you include more features in a design, the number of these stages may increase dramatically. Even a relatively simple change in the design may result in a significant increase in the time required to build using conventional methods. AM can, therefore, be seen as a way to more effectively predict the amount of time to fabricate models, regardless of what changes may be implemented during this formative stage of the product development.

Similarly, the number of processes and resources required can be significantly reduced when using AM. If a skilled craftsman was requested to build a prototype according to a set of CAD drawings, he may find that he must manufacture the part in a number of stages. This may be because he must employ a variety of construction methods, ranging from hand carving, through molding and forming techniques, to CNC machining. Hand carving and similar operations are tedious, difficult, and prone to error. Molding technology can be messy and obviously requires the building of one or more molds. CNC machining requires careful planning and a sequential approach that may also require construction of fixtures before the part itself can be made. All this presupposes that these technologies are within the repertoire of the craftsman and readily available.

AM can be used to remove or at least simplify many of these multi-stage processes. With the addition of some supporting technologies like silicon-rubber molding, drills, polishers, grinders, etc. it can be possible to manufacture a vast range of different parts with different characteristics. Workshops which adopt AM technology can be much cleaner, more streamlined and more versatile than before.

DISTINCTION BETWEEN AM AND CNC MACHINING

As mentioned in the discussion on Automated Fabrication, AM shares some of its DNA with Computer Numerical Controlled machining technology. CNC is also computer-based technology that is used to manufacture products. CNC differs mainly in that it is primarily a subtractive rather than additive process, requiring a block of material that must be at least as big as the part that is to be made. This section discusses a range of topics where comparisons between CNC machining and AM can be made. The purpose is not really to influence choice of one technology over another rather than to establish how they may be implemented for different stages in the product development process, or for different types of products.

- **MATERIAL**

AM technology was originally developed around polymeric materials, waxes and paper laminates. Subsequently, there has been introduction of composites, metals, and ceramics. CNC machining can be used for soft materials, like medium-density fibreboard (MDF), machinable foams, machinable waxes, and even some polymers. However, use of CNC to shape softer materials is focused on preparing these parts for use in a multistage process like casting. When using CNC machining to make final products, it works particularly well for hard, relatively brittle materials like steels and other metal alloys to produce high accuracy parts with well-defined properties. Some AM parts, in contrast, may have voids or anisotropy that are a function of part orientation, process parameters or how the design was input to the machine, whereas CNC parts will normally be more homogeneous and predictable in quality.

- **SPEED**

High speed CNC machining can generally remove material much faster than AM machines can add a similar volume of material. However, this is only part of the picture, as AM technology can be used to produce a part in a single stage. CNC machines require considerable setup and process planning, particularly as parts become more complex in their geometry. Speed must therefore be considered in terms of the whole process rather than just the physical interaction of the part material. CNC is likely to be a multistage manufacturing process, requiring repositioning or relocation of parts within one machine or use of more than one machine. To make a part in an AM machine, it may only take a few hours; and in fact, multiple parts are often batched together inside a single AM build. Finishing may take a few days if the requirement is for high quality. Using CNC machining, this same process may take weeks.

- **COMPLEXITY**

As mentioned above, the higher the geometric complexity, the greater the advantage AM has over CNC. If CNC is being used to create a part directly in a single piece, then there are some geometric features that cannot be fabricated. Since a machining tool must be carried in a spindle, there may be certain accessibility constraints or clashes preventing the tool from being located on the machining surface of a part. AM processes are not constrained in the same way and undercuts and internal features can be easily built without specific process planning. Certain parts cannot be fabricated by CNC unless they are broken up into components and reassembled at a later stage. Consider, for example, the possibility of machining a ship inside a bottle. How would you machine the ship while it is still inside the bottle? Most likely you would machine both elements separately and work out a way to combine them together as an assembly process. With AM you can build the ship and the bottle all at once. An expert in machining must therefore analyze each part prior to it being built to ensure that it indeed can be built and to determine what methods need to be used. While it is still possible that some parts cannot be built with AM, the likelihood is much lower and there are generally ways in which this may be overcome without too much difficulty.

- **ACCURACY**

AM machines generally operate with a resolution of a few tens of microns. It is common for AM machines to also have variable resolution along different orthogonal axes. Typically, the vertical build axis corresponds to layer thickness and this would be of a lower resolution compared with the two axes in the build plane. Accuracy in the build plane is determined by the positioning of the build mechanism, which will normally involve gearboxes and motors of some kind. This mechanism may also determine the minimum feature size as well. For example, SL uses a laser as part of the build mechanism that will normally be positioned using galvanometric mirror drives. The resolution of the galvanometers would determine the overall dimensions of parts built, while the diameter of the laser beam would determine the minimum wall thickness. The accuracy of CNC machines on the other hand is mainly determined by a similar positioning resolution along all three orthogonal axes and by the diameter of the rotary cutting tools. There are factors that are defined by the tool geometry, like the radius of internal corners, but wall thickness can be thinner than the tool diameter since it is a subtractive process. In both cases very fine detail will also be a function of the properties of the build material.

- **GEOMETRY**

AM machines essentially break up a complex, 3D problem into a series of simple 2D cross-sections with a nominal thickness. In this way, the connection of surfaces in 3D is removed and continuity is determined by how close the proximity of one cross-section is with an adjacent one. Since this cannot be easily done in CNC, machining of surfaces must normally be generated in 3D space. With simple geometries, like cylinders, cuboids, cones, etc., this is a relatively easy process defined by joining points along a path; these points being quite far apart and the tool orientation being fixed. In cases of freeform surfaces, these points can become very close together with many changes in orientation. Such geometry can become extremely difficult to produce with CNC, even with 5-axis control or greater.

Undercuts, enclosures, sharp internal corners and other features can all fail if these features are beyond a certain limit. Consider, for example, the features represented in the part in Fig. 3. Many of them would be very difficult to machine without manipulation of the part at various stages.

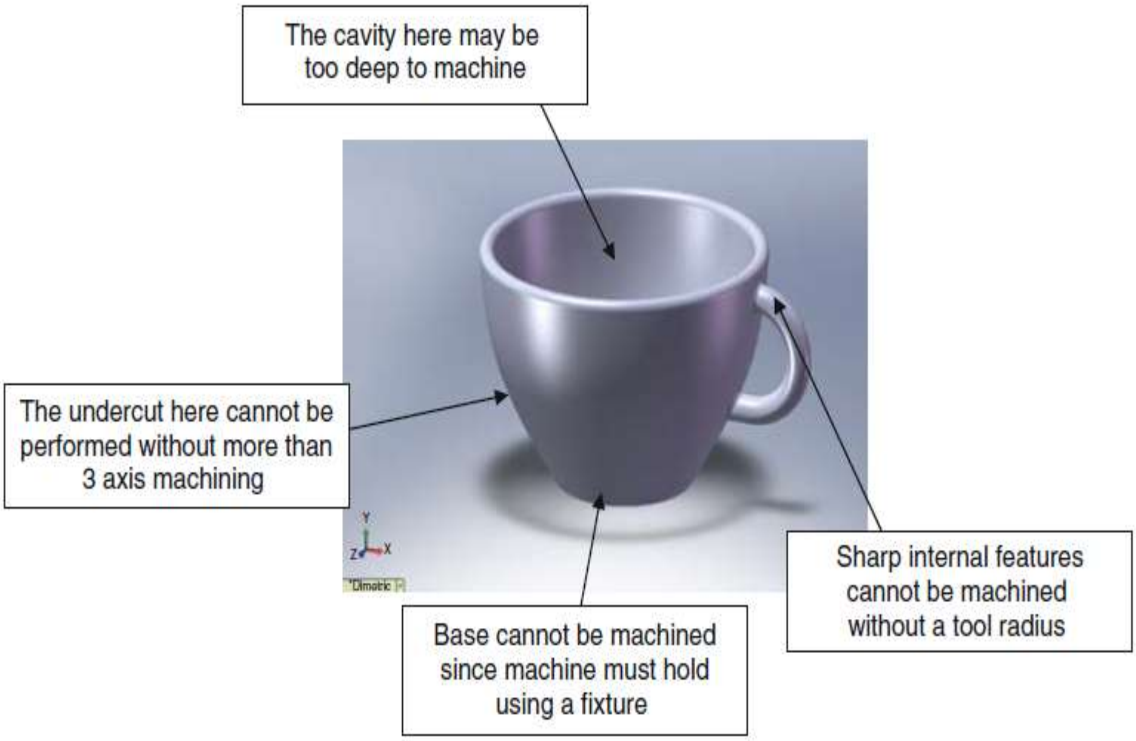

Fig. 3 Features that represent problems using CNC machining

- **PROGRAMMING**

Determining the program sequence for a CNC machine can be very involved, including tool selection, machine speed settings, approach position, and angle, etc. Many AM machines also have options that must be selected, but the range, complexity and implications surrounding their choice are minimal in comparison. The worst that is likely to happen in most AM machines is that the part will not be built very well if the programming is not done properly. Incorrect programming of a CNC machine could result in severe damage to the machine and may even be a safety risk.

OTHER RELATED TECHNOLOGIES

The most common input method for AM technology is to accept a file converted into the STL file format originally built within a conventional 3D CAD system. There are, however, other ways in which the STL files can be generated and other technologies that can be used in conjunction with AM technology. This section will describe a few of these are

1. Reverse Engineering Technology
2. Computer-Aided Engineering
3. Haptic-Based CAD

REVERSE ENGINEERING TECHNOLOGY

More and more models are being built from data generated using reverse engineering (RE) 3D imaging equipment and software. In this context, RE is the process of capturing geometric data from another object. This data is usually initially available in what is termed “point cloud” form, meaning an unconnected set of points representing the object surfaces. These points need to be connected together using RE software like Geomagic [6], which may also be used to combine point clouds from different scans and to perform other functions like hole-filling and smoothing. In many cases, the data will not be entirely complete. Samples may, for example, need to be placed in a holding fixture and thus the surfaces adjacent to this fixture may not be scanned. In addition, some surfaces may obscure others, like with deep crevices and internal features; so that the representation may not turn out exactly how the object is in reality.

Engineered objects would normally be scanned using laser-scanning or touchprobe technology. Objects that have complex internal features or anatomical models may make use of Computerized Tomography (CT), which was initially developed for medical imaging but is also available for scanning industrially produced objects. This technique essentially works in a similar way to AM, by scanning layer by layer and using software to join these layers and identify the surface boundaries. Boundaries from adjacent layers are then connected together to form surfaces. The advantage of CT technology is that internal features can also be generated. High energy X-rays are used in industrial technology to create high resolution images of around 1 mm. Another approach that can help digitize objects is the Capture Geometry Inside technology that also works very much like a reverse of AM technology, where 2D imaging is used to capture cross-sections of a part as it is machined away layer by layer. Obviously, this is a destructive approach to geometry capture so it cannot be used for every type of product. AM can be used to reproduce the articles that were scanned, which essentially would form a kind of 3D facsimile (3D Fax) process. More likely, however, the data will be modified and/or combined with other data to form complex, freeform artifacts that are taking advantage of the “complexity for free” feature of the technology. An example may be where individual patient data is combined with an engineering design to form a customized medical implant.

DEVELOPMENT OF ADDITIVE MANUFACTURING TECHNOLOGY

INTRODUCTION

Additive Manufacturing (AM) technology came about as a result of developments in a variety of different 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 prototyping.

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, ENIAC and EDSAC 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. 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.

That remarkable misjudgement may have caused Olsen to lose his job not long afterwards.

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 4 shows how the above-mentioned technologies are integrated to form an AM machine.

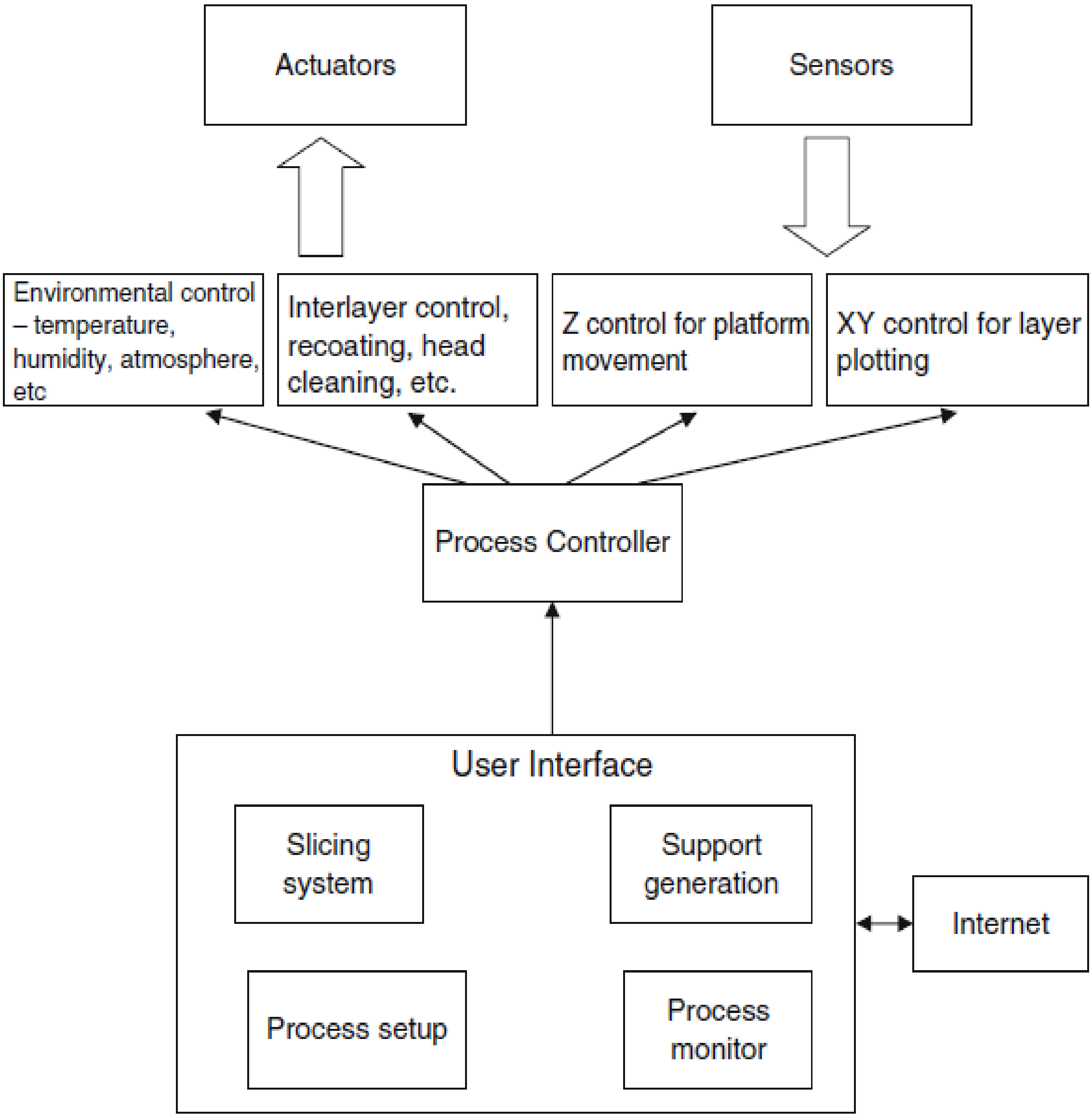

Fig. 4 General integration of an AM machine

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 (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 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 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.

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 mechanical engineering, 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 Manufacture (CAM). CAM represents a channel for converting the virtual images 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 fuelled 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 can not 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.

CAD technology has rapidly improved along the following lines:

1. **Realism:**

With lighting and 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.

2. **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) have 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.

3. **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, 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.

4. **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.

5. **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.

6. **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.

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. 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 5).

Fig. 5 A CAD model on the left converted into STL format on the right

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. 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.

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.

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 build-up 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 many manufacturers have more recently switched to solid-state technology, which provides greater efficiency, lifetime, and reliability.

2. PRINTING TECHNOLOGIES

Ink-jet or droplet printing technology has rapidly developed in recent years. Improvements in resolution and reduction in costs has meant that high-resolution printing, often 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.6), it is possible to produce low-cost, high-resolution, high-throughput AM technology. In the same way that other AM technologies have applied the mass-produced laser technology, other technologies have piggy-backed upon the larger printing industry.

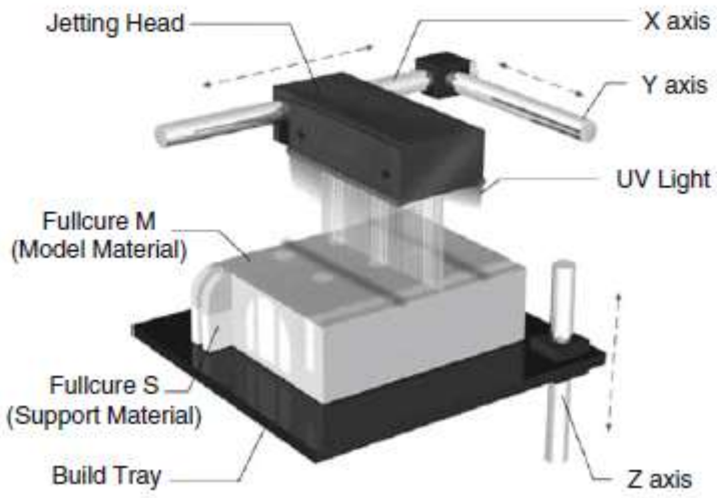

Fig. 6 Printer technology used on an AM machine (photo courtesy of Object)

3. Programmable Logic Controllers

The input CAD models for AM are large data files generated using standard computer technology. Once they are on theAMmachine, however, these files are reduced to a series of process stages that require sensor input and signaling of actuators. This is process and machine control that often is 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, is much easier using building blocks based around modern PLCs for coordinating and controlling the various steps in the machine process.

4. Materials

Earlier AM technologies were built around materials that were already available and that had been developed to suit other processes. However, the 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 melting processes degraded quickly within the machine and many of the materials used 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 and it is even possible to process metals with some AM technologies.
In turn, these new materials have resulted in the processes being tuned to produce higher temperature materials, smaller feature sizes, and faster throughput.

5. **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 development of hybrid prototyping technologies, such as Space Puzzle Molding that use both high-speed machining and additive techniques for making large, complex and durable molds and components, as shown in Fig.7 illustrate how the two can be used interchangeably to take advantage of the benefits of both technologies.

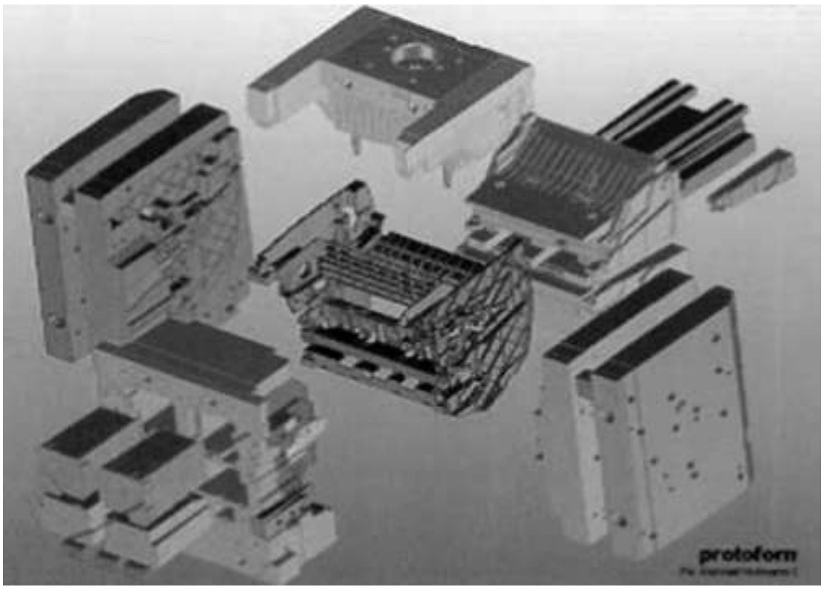

Fig. 7 Space Puzzle Molding, where molds are constructed in segments for fast and easy fabrication and assembly

For geometries that can be machined using a single set-up 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.

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; and certainly, all commercial systems work that way, primarily due to the simplification of building 3D objects. Using 2D representations to represent cross-sections of a more complex 3D feature has been used 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.8

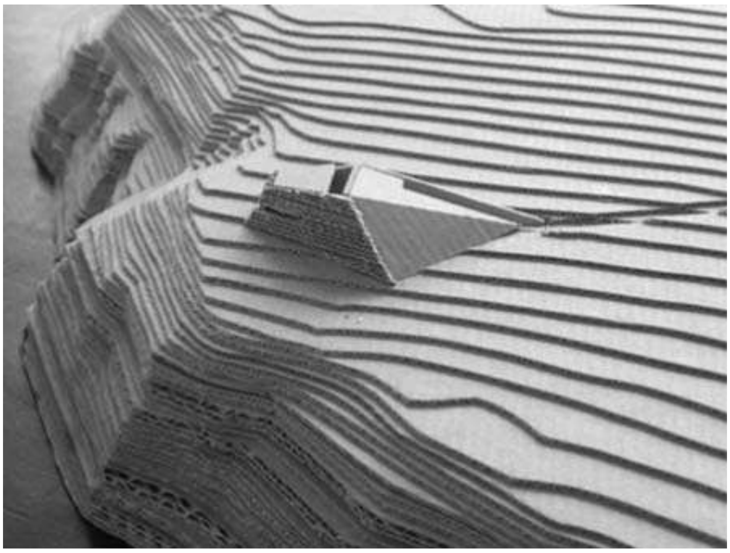

Fig. 8 An architectural landscape model, illustrating the use of layers

The concept is 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.

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. Another approach is to collect processes together according to the type of raw material input. 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 Object). It is probably inappropriate, therefore, to use a single classification approach. An excellent and comprehensive classification method is described by Pham, which uses a two-dimensional classification method as shown in Fig. 9.

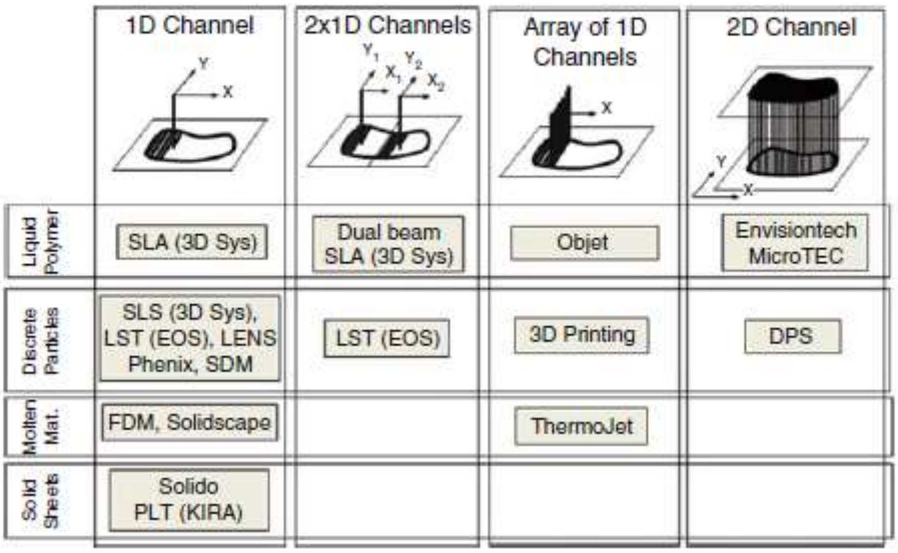

Fig. 9 Layered Manufacturing (LM) processes as classified by Pham

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 Micro-mirror Devices (DMDs) and high resolution display technology, capable of exposing an entire surface in a single pass. However, just using this classification 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 using an extrusion-based technology. This fits well as a 1D channel but the material is not explicitly listed, although it could be argued that the composite is extruded as a molten material. Furthermore, there may come systems in the future 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.

1. Liquid Polymer Systems
2. Discrete Particle Systems
3. Molten Material Systems
4. Solid Sheet Systems
5. New AM Classification Schemes

METAL SYSTEMS

One of the most important recent developments in AM has been the proliferation of direct metal processes. Machines like the EOSint-M and Laser-Engineered Net Shaping (LENS) have been around for a number of years. Recent additions from other companies and improvements in laser technology, machine accuracy, speed, and cost have opened up this market.

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 approaches, particularly the Ultrasonic Consolidation process from the Solidica, USA, which uses sheet metal laminates that are ultrasonically welded together. 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 Electron Beam Melting (EBM) process by the Swedish company Arcam. Another approach is the LENS powder delivery system used by Optomec. 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.

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 object 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 object 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 Strat conception approach, 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, 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 Strat conception. 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 Shaped Deposition Manufacturing (SDM), developed mainly at Stanford and Carnegie- Mellon Universities in the USA. 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.

MILESTONES IN AM DEVELOPMENT

We can look at the historical development of AM in a variety of different ways. The origins may be difficult to properly define and there was certainly quite a lot of activity in the 1950s and 1960s, but development of the associated technology (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 US (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 3D Systems. This was the first company to commercialize AM technology with the Stereolithography apparatus (Fig.10).

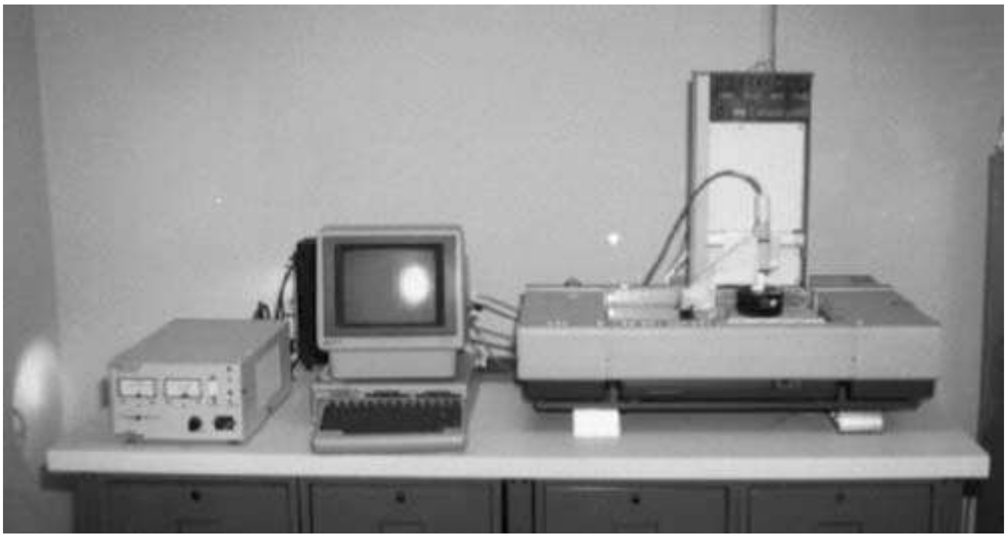

Fig. 10 The first AM technology from Hull, who founded 3D systems

Further patents came along in 1986, resulting in three more companies, Helisys (Laminated Object Manufacture or LOM), Cubital (with Solid Ground Curing, SGC), and DTM with their Selective Laser Sintering (SLS) process. It's interesting to note neither Helisys or 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 is ZCorp, which focuses mainly on lowcost technology.

Ink-jet 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 the Objet Company 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 interesting to note that some 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 four variants from Singapore, China, Japan, and Israel. The most recent Solido process laminates polymer sheets together rather than the paper sheets used in the original LOM machine. Perhaps this is a better choice of material and perhaps the technology is in a better position to become successful now compared with the original machines that are 20-years old. Another example may be 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.

ADDITIVE MANUFACTURING PROCESS CHAIN

INTRODUCTION

Every product development process involving an Additive Manufacturing machine requires the operator to go through a set sequence of tasks. Easy-to-use "desktop" or "3D printing" machines emphasize the simplicity of this task sequence. These desktop machines are characterized by their low cost, simplicity of use, and ability to be placed in an office environment. For these machines each step is likely to have few options and require minimal effort. However, this also means that there are generally fewer choices, with perhaps a limited range of materials and other variables to experiment with. The larger and more versatile machines are more capable of being tuned to suit different user requirements and therefore are more difficult to operate, but with a wider variety of possible results and effects that may be put to good use by an experienced operator. Such machines also usually require more careful installation in workshop environments. The objective is to allow the reader to understand how these machines may differ and also to see how each task works and how it may be exploited to the benefit of higher quality results.

THE EIGHT STEPS IN ADDITIVE MANUFACTURE

This above-mentioned sequence of steps is generally appropriate to all AM technologies. There will be some variations dependent on which technology is being used and also on the design of the particular part. Some steps could be quite involved for some machines but may be trivial for others. While most of the initial discussion below is with respect to production of polymer parts, most steps can be generalized to metal systems as well.

Step 1: Conceptualization and CAD

The first step in any product development process is to come up with some idea as to how the product will look and function. Conceptualization can take many forms, from textual and narrative descriptions to sketches and representative models. If AM is to be used, the product description must be in a form that allows a physical model to be made. It may be that AM technology will not be used to realize the final product, but for complex products there are likely to be many stages in the development process where models can be used. For these purposes it is therefore important that the model description be entered into a computer. AM technology would not exist if it were not for 3D CAD. Only after we gained the ability to represent solid objects in computers were we able to develop technology to physically reproduce such objects. Initially, this was the principle surrounding CNC machining technology in general. AM can thus be described as a direct or streamlined Computer Aided Design to Computer Aided Manufacturing (CAD/CAM) process. Unlike most other CAD/CAM technologies, there is little or no intervention between the design and manufacturing stages for AM.

The generic AM process must therefore start with 3D CAD information, as shown in Fig. 11. There may be a variety of ways as to how the 3D source data can be created. This model description could be generated by a computer user, using a user-interface, or via reverse engineering technologies. Most 3D CAD systems are solid modeling systems with some surface modeling components. That is to say that solid models are sometimes constructed by combining surfaces together or by adding thickness to a surface. In the past, 3D CAD modeling software had difficulty creating fully enclosed solid models, and often models would appear to the casual observer to be enclosed but in fact were not. Such models could result in unpredictable output from AM machines, with different AM technologies treating gaps in different ways.

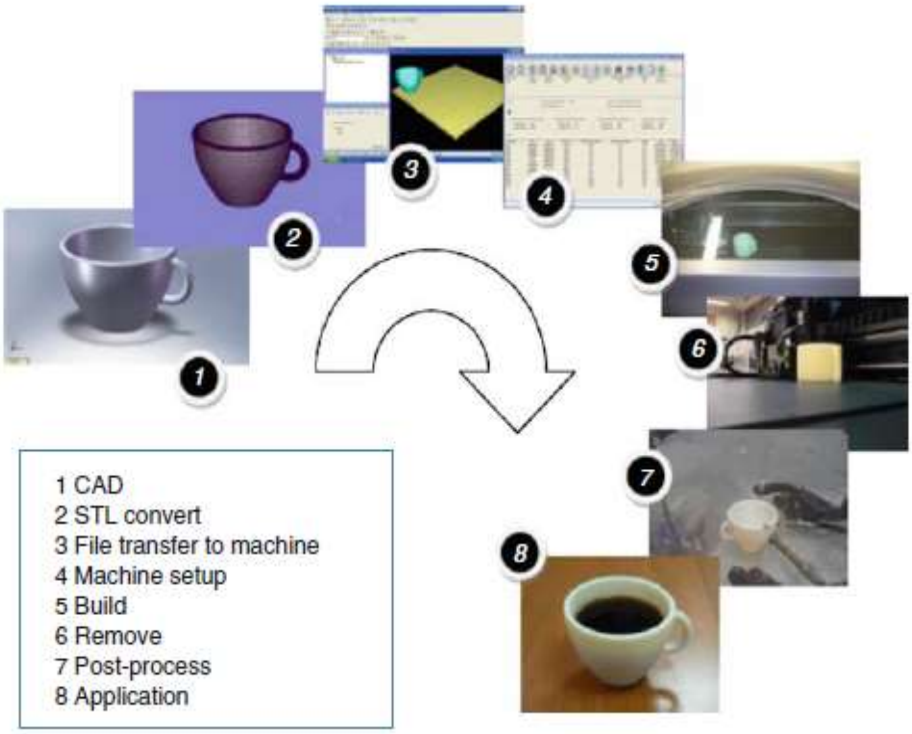

Fig. 11 The eight stages of the AM process

Today, CAD software has developed to the extent that there are very few problems with surface discontinuities, with extensive checking and correction software built in to most systems. Most CAD packages treat surfaces as construction tools that are used to act on solid models and this has the effect of maintaining the integrity of the solid data. Provided it can fit inside the machine, typically any CAD model can be made using AM technology without too many difficulties.

However, there still remains some older or poorly developed 3D CAD software that may result in solids that are not fully enclosed and produce unreliable AM output. Problems of this manner are normally detected once the CAD model has been converted into the STL format for building using AM technology.

Step 2: Conversion to STL

Nearly every AM technology uses the STL file format. The term STL was derived from STereoLithograhy, which was the first commercial AM technology from 3D Systems in the 1990s. Considered a de facto standard, STL is a simple way of describing a CAD model in terms of its geometry alone. It works by removing any construction data, modeling history, etc., and approximating the surfaces of the model with a series of triangular facets. The minimum size of these triangles can be set within most CAD software and the objective is to ensure the models created do not show any obvious triangles on the surface. The triangle size is in fact calculated in terms of the minimum distance between the plane represented by the triangle and the surface it is supposed to represent. In other words, a basic rule of thumb is to ensure that the minimum triangle offset is smaller than the resolution of the AM machine. The process of converting to STL is automatic within most CAD systems, but there is a possibility of errors occurring during this phase. There have therefore been a number of software tools developed to detect such errors and to rectify them if possible.

STL file repair software, like the MAGICS software from the Belgian company Materialise, is used when there are problems with the file generated by the CAD system that may prevent the part from being built correctly. With complex geometries, it may be difficult to detect such problems when inspecting the CAD or the subsequently generated STL data. If the errors are small then they may even go unnoticed until after the part has been built. Such software may therefore be applied as a checking stage to ensure that there are no problems with the STL file data before the build is performed.

Since STL is essentially a surface description, the corresponding triangles in the files must be pointing in the correct direction; in other words, the surface normal vector associated with the triangle must indicate which side of the triangle is outside vs. inside the part. The cross-section that corresponds to the part layers of a region near an inverted normal vector may therefore be the inversion of what is desired.

Additionally, complex and highly discontinuous geometry may result in triangle vertices that do not align correctly. This may result in gaps in the surface. Various AM technologies may react to these problems in different ways. Some machines may process the STL data in such a way that the gaps are bridged. This bridge may not represent the desired surface, however, and it may be possible that additional, unwanted material may be included in the part.

While most errors can be detected and rectified automatically, there may also be a requirement for manual intervention. Software should therefore highlight the problem, indicating what is thought to be inverted triangles for instance. Since geometries can become very complex, it may be difficult for the software to establish whether the result is in fact an error or something that was part of the original design intent.

Step 3: Transfer to AM Machine and STL File Manipulation

Once the STL file has been created, it can be sent directly to the target AM machine. Ideally, it should be possible to press a “print” button and the machine should build the part straight away. This is not usually the case however and there may be a number of actions required prior to building the part.

The first task would be to verify that the part is correct. AM system software normally has a visualization tool that allows the user to view and manipulate the part. The user may wish to reposition the part or even change the orientation to allow it to be built at a specific location within the machine. It is quite common to build more than one part in an AM machine at a time. This may be multiples of the same part (thus requiring a copy function) or completely different STL files. STL files can be linearly scaled quite easily. Some applications may require the AM part to be slightly larger or slightly smaller than the original to account for process shrinkage or coatings; and so, scaling may be required prior to building. Applications may also require that the part be identified in some way and some software tools have been developed to add text and simple features to STL formatted data for this purpose. This would be done in the form of adding 3D embossed characters. More unusual cases may even require segmentation of STL files (e.g., for parts that may be too large) or even merging of multiple STL files. It should be noted that not all AM machines will have all the functions mentioned here, but numerous STL file manipulation software tools are available for purchase or, in some cases, for free download.

Step 4: Machine Setup

All AM machines will have at least some setup parameters that are specific to that machine or process. Some machines are only designed to run perhaps one or two different materials and with no variation in layer thickness or other build parameters.

These types of machine will have very few setup changes to make from build to build. Other machines are designed to run with a variety of materials and may also have some parameters that require optimization to suit the type of part that is to be built, or permit parts to be built quicker but with poorer layer resolution, for example. Such machines can have numerous setup options available. It is common in the more complex cases to have default settings or save files from previously defined setups to help speed up the machine setup process and to prevent mistakes being made. Normally, an incorrect setup procedure will still result in a part being built. The final quality of that part may, however, be unacceptable.

Step 5: Build

Although benefitting from the assistance of computers, the first few stages of the AM process are semi-automated tasks that may require considerable manual control, interaction, and decision making. Once these steps are completed, the process switches to the computer-controlled building phase. This is where the previously mentioned layer-based manufacturing takes place. All AM machines will have a similar sequence of layer control, using a height adjustable platform, material deposition, and layer cross-section formation. Some machines will combine the material deposition and layer formation simultaneously while others will separate them. All machines will repeat the process until either the build is complete or there is no source material remaining. In either case, the machine will alert the user to take action.

Step 6: Removal and Clean up

Ideally, by this stage the output from the AM machine should be ready for use. While sometimes this may be the case, more often than not parts will still require a significant amount of manual finishing before they are ready for use. In all cases, the part must be either separated from a build platform on which the part was produced or removed from excess build material surrounding the part. Some AM processes use additional material other than that used to make the part itself (secondary support materials). This material will be used to aid the building process in some way. Later descriptions of the AM processes will discuss the need for these support structures to help keep the part from collapsing or warping during the building process. At this stage, it is not necessary to understand exactly how support structures work, but it is necessary to know that they need to be dealt with. While some processes have been developed to produce easy-to-remove supports, there is still often a significant amount of manual work required at this stage. There is also a degree of manual skill required since mishandling of parts and poor technique in support removal can result in a low quality output. Different AM parts have different cleanup requirements, but suffice it to say that all processes have some requirement at this stage. The cleanup stage may also be considered as the initial part of the post-processing stage.

Step 7: Post-process

Post-processing refers to the (usually manual) stages of finishing the parts for application purposes. This may involve abrasive finishing, like polishing and sandpapering, or application of coatings. This stage in the process is very application-specific. Some applications may only require a minimum of postprocessing; taking advantage of the speed at which the parts are made. Other applications may require very careful handling of the parts to maintain good precision and finish. Different AM processes have different results in terms of accuracy and material properties. Some processes produce relatively fragile components that may require the use of infiltration and/or surface coatings to strengthen the final part. As already stated, this is primarily a manual task due to the complexity of most AM parts. However, some of the tasks can benefit from the use of power tools and additional equipment, like polishing tubs or drying and baking ovens.

Step 8: Application

Following post-processing, parts are ready for use. It should be noted that, although parts may be made from similar materials to those available from other manufacturing processes (like molding and casting), parts may not behave according to standard material specifications. Some AM processes inherently create parts with small voids or bubbles trapped inside them, which could be the source for part failure under mechanical stress. In addition, some processes may cause the material to degrade during build or for materials not to bond, link, or crystallize in an optimum way. In almost every case, the properties are anisotropic (different properties in different direction). This may result in parts that behave differently than if they were made using a more conventional manufacturing approach. However, AM materials and processes are improving all the time, and many applications do not require high performance from many of their components. The number of applications for the output from AM processes is therefore constantly increasing.

VARIATIONS FROM ONE AM MACHINE TO ANOTHER

The above generic process steps can be applied to every commercial AM technology. As has been noted, different technologies may require more or less attention for a number of these stages. Here we discuss the implications of these variations, not only from process to process but also in some cases within a specific technology.

The nominal layer thickness for most machines is around 0.1 mm. However, it should be noted that this is just a rule of thumb. For example, the layer thickness for most FDM Dimension machines is 0.254 mm. Contrast that with standard layer thicknesses between 0.05 and 0.1 mm for SL technology. Many technologies have the capacity to vary the layer thickness. The reasoning is that thicker layer parts are quicker to build but are less precise. This may not be a problem for some applications where it may be more important to make the parts as quickly as possible.

Fine detail in a design may cause problems with some AM technologies, such as wall thickness; particularly if there is no choice but to build the part vertically. This is because even though positioning within the machine may be very precise, there is a finite dimension to the droplet size, laser diameter, or extrusion head that essentially defines the finest detail or thinnest wall that can be fabricated.

There are other factors that may not only affect the choice of process but also influence some of the steps in the process chain. In particular, the use of different materials even within the same process may affect the time, resources, and skill required to carry out a stage. For example, the use of water soluble supports in FDM may require specialist equipment but will also provide better finish to parts with less hand finishing required than when using conventional supports. Alternatively, some polymers require special attention, like the use (or avoidance) of particular solvents or infiltration compounds. A number of processes benefit from application of sealants or even infiltration of liquid polymers. These materials must be compatible with the part material both chemically and mechanically. Post-processing that involves heat must include awareness of the heat resistance or melting temperature of the materials involved. Abrasive or machining-based processing must also require knowledge of the mechanical properties of the materials involved. If considerable finishing is required, it may also be necessary to include an allowance in the part geometry, perhaps by using scaling of the STL file or offsetting of the part’s surfaces, so that the part does not become worn away too much.

Variations between AM technologies will become clarified further in the following chapters, but a general understanding can be had by considering whether the build material is processed as a powder, molten material, solid sheet, vat of liquid photopolymer, or ink-jet deposited photopolymer.

METAL SYSTEMS

As previously mentioned, operation of metal-based AM systems is conceptually similar to polymer systems. However, the following points are worth considering.

i. The Use of Substrates

Most metal systems make use of a base platform or substrate onto which parts are built and from which they must be removed using machining, wire cutting, or a similar method. The need to attach the parts to a base platform is mainly because of the high temperature gradients between the temporarily molten material and its surroundings. If the material did not adhere to a solid platform then there would be a tendency for the part to warp as it cools, which means further layers of powder cannot be spread evenly. Therefore, even though these are mainly powder-based systems, there is still a need for supports.

ii. Energy Density

The energy requirements for melting metals to over 1,000_C is obviously much higher than heating polymers to around 200_C. Heat shielding, insulation, temperature control, and atmospheric control are much more stringent than in the lower cost polymer systems.

iii. Weight

Metal powder systems may process lightweight titanium powders but they also process high-density tool steels. The powder handling technology must be capable of withstanding the mass of these materials. This means that power requirements for positioning and handling equipment must be quite substantial or gear ratios must be high (and corresponding travel speeds lower) to deal with these tasks.

iv. Accuracy

Metal powder systems are generally at least as accurate as corresponding polymer powder systems. Surface finish is characteristically grainy but part density and part accuracy are very good. Surface roughness is in the order of a few tens to a few hundreds of microns depending on the process and can be likened in general appearance to precision casting technology. For metal parts, this is often not satisfactory and at least some shot-peening is required to smooth the surface. Key mating features on metal parts often require surface machining or grinding. The part density will be high (generally over 99%), although some voids may still be seen.

v. Speed

Since there are heavy requirements on the amount of energy to melt the powder particles and to handle the powders within the machine, the build speed is generally slower than a comparable sized polymer system. Laser powers are not excessively high, usually just a few hundred watts (polymer systems start at around 50 watts of laser power). This means that the laser scanning speed is quite low to ensure enough energy is delivered to the powder.

MAINTENANCE OF EQUIPMENT

While numerous stages in the AM process have been discussed, it is important to realize that many machines require careful maintenance. Some machines use fragile laser or printer technology that must be carefully monitored and that should preferably not be used in a dirty or noisy (both electrical noise and mechanical vibration) environment. Similarly, many of the feed materials require careful handling and should be used in low humidity conditions. While machines are designed to operate unattended, it is important to include regular checks in the maintenance schedule. As indicated earlier, AM processes fall outside of many materials and process standards. However, many machine vendors recommend and provide test patterns that should be used periodically to confirm that the machines are operating within acceptable limits.

Laser-based systems are generally expensive because of the cost of the laser itself. Furthermore, maintenance of a laser can be very expensive since the expected lifetime can be as low as 4,000 operating hours for tube lasers and up to more than 15,000 h for solid state lasers. Printheads are also components that have finite lifetimes for the printer-based systems. The fine nozzle dimensions and the use of relatively high viscosity fluids mean they are quite prone to clogging and contamination effects. Replacement costs are, however, generally quite low.

MATERIALS HANDLING ISSUES

In addition to the machinery, AM materials often require careful handling. The raw materials used in some AM processes have limited shelf-life and must also be kept in conditions that prevent them from chemical reaction or degradation. Exposure to moisture and to excess light should be avoided. Most processes use materials that can be used for more than one build. However, it may be that this could degrade the material if used many times over and therefore a procedure for maintaining consistent material quality through recycling should also be observed.

While there are some health concerns with extended exposure to some photopolymer resins, most AM polymer raw materials are safe to handle. Powder materials may in general be medically inert, but excess amounts of powder can make the workplace slippery, contaminate mechanisms, etc. This may cause particular problems if machines are to be used in a design center environment rather than in a workshop. AM system vendors have spent considerable effort to simplify and facilitate material handling. Loading new materials is now often a procedure that can be done offline or with minimal changeover time so that machines can run continuously. Software systems are often tuned to the materials so that they can recognize different materials and adjust build parameters accordingly.

Many materials are carefully tuned to work with a specific AM technology. There are often warranty issues surrounding the use of third party materials that users should be aware of since there is a potential danger to the equipment or reduction in part quality. For example, SLS powders may have additives that prevent degradation due to oxidation since they are kept at elevated temperatures for long periods of time. Also, FDM filaments are extruded to a very tight diametric tolerance not normally available from conventional extruders. Since the FDM material drive pushes the filament through the machine, variations in diameter may cause slippage. Furthermore, build parameters are designed around the standard materials used. Since there are huge numbers of material formulations, changing one material for another, even though they are apparently the same, may still require careful build setup.

Some machines allow the user to recycle some or all of the material from a build that did not form the earlier part. This is particularly true with the powder-based systems. Also SL resins can be reused. However, there may be artifacts and other contaminants in the recycled materials and it is important to carefully inspect, sift, or sieve the material before returning it to the machine. Many SLS builds have been spoilt, for example, by hairs that have come off a paintbrush used to clean the parts from a previous build.

DESIGN FOR AM

Designers and operators should consider a number of build-related factors when considering the set-up of an AM, including the following sections.

1. **Part Orientation**

If a cylinder was built on its end, then it would consist of a series of circular layers built on top of each other. Although layer edges may not be precisely vertical in all AM processes, the result would still normally be a very well defined cylinder with a relatively smooth edge. The same cylinder built on its side, so that the circular end is vertical, will have distinct layer patterning on the sides. This will result in less accurate reproduction of the original CAD data with a poorer esthetic appearance. Orientation of the part within the machine can affect part accuracy. Since many parts will have complex features along multiple axes, there may not be an ideal orientation for a particular part. Furthermore, it may be more important to maintain the geometry of some features when compared with others, so correct orientation may be a judgment call. This judgment may also be in contrast with other factors like the time it takes to build a part (e.g., taller builds take longer than shorter ones so high aspect ratio parts may be better built lying down), whether a certain orientation will generate more supports, or whether certain surfaces should be built face-up to ensure good surface finish in areas that are not in contact with support structures.

2. Removal of Supports

For those technologies that require supports it is a good idea to try and minimize the amount. No matter which system you use, any down-facing surface will be marginally poorer in surface quality than surfaces that point upwards and to the outside. Supports exacerbate this situation. Wherever the supports meet the part there will be small marks and reducing the number of supports would make the part more accurate and reduce the amount of part clean-up and post-process finishing.

However, as mentioned above, some surfaces may not be as important as others and so positioning of the part must be weighed against the relative importance of an affected surface.

Parts that require supports may also require planning for their removal. Supports may be located in difficult to reach regions within the part. For example, a hollow cylinder with end caps built vertically will require supports for the top surface. However, if there is no access hole then these supports cannot be removed. Inclusion of access holes (which could be plugged later) is a possible solution to this, as may be breaking up the part so the supports can be removed before reassembly. Similarly, SL parts may require drain holes for any trapped liquid resin.

3. Hollowing Out Parts

Parts that have thick walls may be designed to include hollow features if this doesn't impede the final functionality. The main benefits of doing this are the reduced time that may result during building of the part and the reduced cost from the use of less material. As mentioned previously, some liquid-based resin systems would require drain holes to remove excess resin from inside the part, which may not be an ideal solution. For these and other systems it may be that a honeycomb- or truss-like internal structure can assist in providing support within the part. All these approaches must be balanced against the additional time that it would take to design such a part. However, there are software systems that would allow this to be done automatically.

4. **Inclusion of Undercuts and Other Manufacturing**

Constraining Features AM models can be used at various stages of the product development process. When evaluating initial designs, focus may be on the esthetics or ultimate functionality of the part. Consideration of how to include manufacturing-related features would have lower priority at this stage. Conventional manufacturing would require considerable planning to ensure that a part is fabricated correctly. Undercuts, draft angles, holes, pockets, etc. must be created in a specific order when using multiplestage processes. While this can be ignored when designing the part for additive processes, it is important not to forget them. Design at this stage may help in optimizing the parts since it would be possible to determine where and what type of rib, boss, and other strengthening approaches should be used on the final part. If the final part is to be injection molded, the AM part can be used to determine the best location for the parting lines in the mold.

5. **Interlocking Features**

AM machines have a finite build volume and large parts may not be capable of being built inside them. A solution may be to break the design up into segments that can fit into the machine and manually assemble them together later. The designer must therefore consider the best way to break up the parts. The regions where the breaks are made can be designed in such a way to facilitate reassembly. Techniques can include incorporation of interlocking features and maximizing surface area so that adhesives can be most effective. Such regions should also be in easy to reach but difficult to observe locations.

This approach of breaking parts up may still be helpful even when they can still fit inside the machine. Consider the design shown in Fig. 3.2. If it was built as a single part, it would take a long time and require a significant amount of supports (as shown in the left-hand figure). If the part were built as two separate pieces the resulting height would be significantly reduced and there would be few supports. The part could be glued together later. This glued region may be slightly weakened, but the individual segments may be stronger. Since the example has a thin wall section, the top of one of the bands will exhibit more stair-stepping and may also be a little weaker than the rest of the part. For the bonded region, it is possible to include large overlapping regions that will enable more effective bonding.

6. **Reduction of Part Count in an Assembly**

There are numerous sections in this book that discuss Direct Digital Manufacturing. This involves the direct manufacture of parts on AM machines for end use. The AM part is therefore toward the end of the product development process and the design does not need to consider alternative manufacturing processes. This in turn means that if the part can be simplified using AM, then this should be done. For example, it is possible to build fully assembled hinge structures by providing clearance around the moving features. What would conventionally be made up of a number of components in an assembly can possibly be designed as a single unit.

7. **Identification Markings/Numbers**

Although AM parts are often unique, it may be difficult for a company to keep track of them when they are possibly building hundreds of parts per week. It is a straightforward process to include identifying features on the parts. This can be done when designing the CAD model but that may not be possible since the models may come from a third party. There are a number of software systems that provide tools for labelling parts by embossing alphanumeric characters onto them as 3D models.

APPLICATION AREAS THAT DON'T INVOLVE CONVENTIONAL CAD MODELING

Additive manufacturing technology opens up opportunities for many applications that do not take the standard product development route. The capability of integrating AM with customizing data or data from unusual sources makes for rapid response and an economical solution. The following sections are examples where nonstandard approaches are applicable.

1. **MEDICAL MODELING**

There is an excellent opportunity to use AM in making models based on an individual person's medical data. The data can be incorporated into the system in a variety of different ways. Such data is based on 3D scanning obtained from systems like Computerized Tomography (CT), Magnetic Resonance Imaging (MRI), 3D ultrasound, etc. This data often needs considerable processing to extract the relevant sections before it can be built as a model or further incorporated into a product design. There are only a handful of software systems that can process the medical data in a suitable way, and a range of applications is starting to emerge. For example, materialise was involved in the development of software that is used in the production of hearing aids. AM technology helps in customizing these hearing aids from data that is collected from the ear canals of individual patients.

2. **REVERSE ENGINEERING DATA**

Medical data from patients is just one application that benefits from being able to collect and process complex surface information. For nonmedical data collection the more common approach is to use laser scanning technology. Such technology has the capacity to faithfully collect surface data from many types of surfaces that are difficult to model because they cannot be easily defined geometrically. Similar to the medical data, although the models can just be reproduced within the AM machine (like a kind of 3D fax machine), the general intention is to merge this data into products.

3. **ARCHITECTURAL MODELING**

Architectural models are usually created to emphasize certain features within a building design and so designs are modified to show textures, colors, and shapes that may not be exact reproductions of the final design. Therefore, architectural packages may require features that are tuned to the AM technology.