Chapter 1
Introduction and Basic Principles

Abstract The technology described in this book was originally referred to as Rapid Prototyping. The term Rapid Prototyping (or RP) is used to describe a process for rapidly creating a system or part representation before final release or commercialization. The emphasis is on creating something quickly for use as a prototype or basis model from which further models and eventually the final product will be derived. In product development, the term Rapid Prototyping describes technologies which create physical prototypes. This text is about technologies which can directly produce objects from digital data. These technologies were first developed for prototyping but are now used for many more purposes.

1.1 What Is Additive Manufacturing?

Additive Manufacturing is the formalized term for what used to be called Rapid Prototyping and what is popularly called 3D Printing. 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 also use the term Rapid Prototyping to describe a process of developing business and software solutions in a piecewise fashion that allows clients and other stakeholders 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 model data. This text is about these latter 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 in particular does not effectively describe more recent applications of the technology.

I. Gibson et al., *Additive Manufacturing Technologies*,
https://doi.org/10.1007/978-3-030-56127-7_1

Improvements in the quality of the output from these machines have meant that there is often 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 Technical Committee within ASTM International agreed that new terminology should be adopted. As a result, ASTM consensus standards now use the term Additive Manufacturing [1] as do most standards bodies worldwide.

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 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 to build the part.

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. 1.1. 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,

Fig. 1.1 CAD image of a teacup with further images showing the effects of building using different layer thicknesses

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 post-processing 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.

1.2 What Are AM Parts Used For?

Throughout this book you will find a wide variety of applications for AM. You will also realize that the number of applications is increasing as the processes develop and improve. Initially, AM was used specifically to create visualization models for products as they were being developed. It is widely known that models can be much more helpful than drawings or renderings in fully understanding the intent of the designer when presenting the conceptual design. While drawings are quicker and easier to create, models are nearly always required in the end to fully validate the design.

Following this initial purpose of simple model making, AM technology has developed over time as materials, accuracy, and the overall quality of the output improved. Models were quickly employed to supply information about what is known as the "3 Fs" of Form, Fit, and Function. The initial models were used to help fully appreciate the shape and general purpose of a design (Form). Improved accuracy in the process meant that components were capable of being built to the tolerances required for assembly purposes (Fit). Improved material properties meant that parts could be properly handled so that they could be assessed according to how they would eventually work (Function).

To say that AM technology is only useful for making models, though, would be inaccurate and undervaluing the technology. AM, when used in conjunction with other technologies to form process chains, can be used to significantly shorten product development times and costs. More recently, some of these technologies have been developed to the extent that the output is suitable for end use. This explains why the terminology has essentially evolved from Rapid Prototyping to Additive Manufacturing.

1.3 The 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 post-processing (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. 1.2).

1.3.1 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 and optical scanning) can also be used to create this representation.

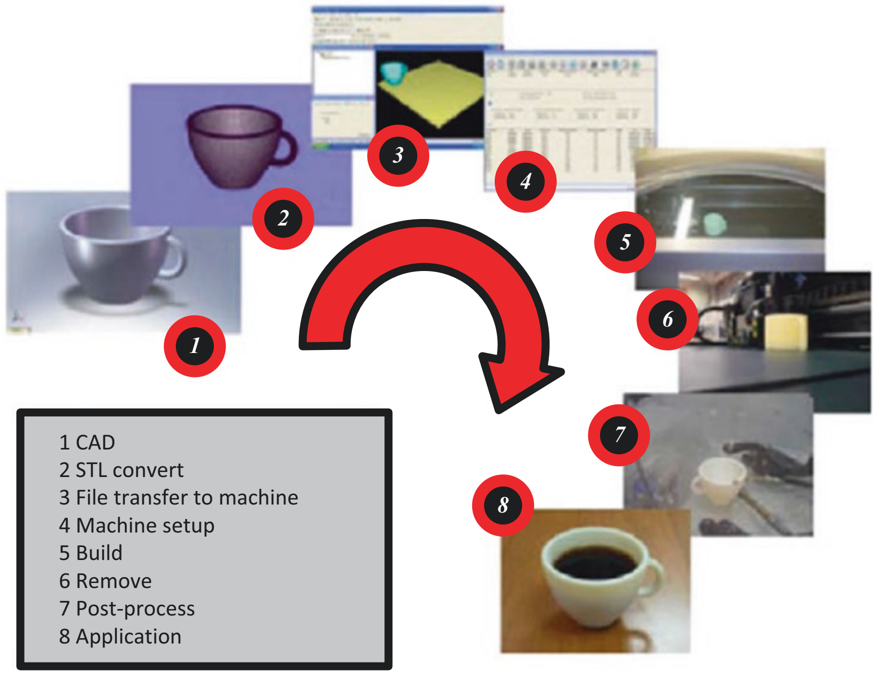

Fig. 1.2 Generic process of CAD to part, showing all eight stages

1.3.2 Step 2: Conversion to STL

Nearly every AM machine accepts the STL file format, which has become a de facto standard, and nowadays 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.

1.3.3 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.

1.3.4 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.

1.3.5 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.

1.3.6 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.

1.3.7 Step 7: Post-Processing

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. They may require priming and painting to give an acceptable surface texture and finish. This step may also involve heat treatment. Post-processing may be costly, laborious, and lengthy if the finishing requirements are very demanding.

1.3.8 Step 8: Application

Parts are now ready for use. This may require them to be assembled together with other mechanical or electronic components to form a final model or product.

While the numerous stages in the AM process have now been discussed, it is important to realize that other steps may be needed for certain machines and processes. For example, certain machine setup software and AM machines may be compatible with native CAD information, and thus the STL file may be skipped. In addition, many AM machines require careful maintenance. Many AM machines use fragile laser or printer technology that must be carefully monitored and that should preferably not be used in a dirty or noisy environment. While machines are generally designed to operate unattended, it is important to include regular checks in the maintenance schedule, and that different technologies and/or applications require different levels of maintenance. There is an increasing use of materials and process standards for AM, and the ASTM F42 Technical Committee on Additive Manufacturing Technologies is working to add more [1]. Maintenance standards may be more strict for certain applications than for others. In addition, many machine vendors recommend and provide test patterns and maintenance guidance that can be used periodically to confirm that machines are operating within acceptable limits.

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

1.4 Why Use the Term Additive Manufacturing?

By now, you should realize that the technology we are referring to is primarily the use of additive processes, combining materials layer-by-layer. The term Additive Manufacturing, or AM, seems to describe this quite well, but there are many other terms which are in use. This section discusses other terms that have been used to describe this technology as a way of explaining the overall purpose and benefits of the technology for product development.

1.4.1 Automated Fabrication (Autofab)

This term was popularized by Marshall Burns in his book of the same name, which was one of the first texts to cover AM technology in the early 1990s [2]. The emphasis here is on the use of automation to manufacture products, thus implying the simplification or removal of manual tasks from the process. Computers and microcontrollers are used to control the actuators and to monitor the system variables. This term can also be used to describe other forms of Computer Numerical Controlled (CNC) machining centers since there is no direct reference as to how parts are built or the number of stages it would take to build them, although Burns does primarily focus on the technologies also covered by this book. Some key technologies are however omitted since they arose after the book was written.

1.4.2 Freeform Fabrication or Solid Freeform Fabrication

The emphasis here is in the capability of the processes to fabricate complex geometric shapes. Sometimes the advantage of these technologies is described in terms of providing "complexity for free," implying that it doesn't particularly matter what the shape of the input object actually is. A simple cube or cylinder would take almost as much time and effort to fabricate within the machine as a complex anatomical structure with the same enclosing volume. The reference to "freeform" relates to the independence of form from the manufacturing process. This is very different from most conventional manufacturing processes that become much more involved as the geometric complexity increases.

1.4.3 Additive Manufacturing or Layer-Based Manufacturing

These descriptions relate to the way the processes fabricate parts by adding material in layers. This is in contrast to machining technology that removes or subtracts material from a block of raw material. It should be noted that some of the processes are not purely additive, in that they may add material at one point but also use subtractive processes at some stage as well. Currently, every commercial process works in a layer-wise fashion. However, there is nothing to suggest that this is an essential approach to use and that future systems may add material in other ways and yet still come under a broad classification that is appropriate to this text. A slight variation on this, Additive Fabrication, is a term that was popularized by Terry Wohlers, a well-known industry consultant in this field and who compiles a widely regarded annual industry report on the state of this industry [3]. However, the term “manufacturing” tends to be the more general term, and, in fact, “Additive Manufacturing” is now the international standard term used to refer to this class of manufacturing processes [4]. Originally approved in 2009 by the ASTM F42 Committee, Additive Manufacturing was adopted as the official name for the technology, along with the names of the seven identified classes of AM processes.

1.4.4 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.

1.4.5 Stereolithography or 3D Printing

These two terms were initially used to describe specific machines. Stereolithography (SL) was termed by the US company 3D Systems [5, 6], and 3D Printing (3DP) was widely used by researchers at MIT [7] who invented an inkjet 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. Recent media interest in the technology has proven this to be true, and the general public is much more likely to know the term 3D Printing than any other term mentioned in this book.

We use Additive Manufacturing or its abbreviation AM throughout this book as the generic term for the suite of technologies covered by this book as this is the terminology used by experts and standards bodies. 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 searching for or reading other literature, the reader must consider the context to best understand what each of these terms means.

1.5 The Benefits of AM

Many people have described AM 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 and that we are experiencing a new industrial revolution. AM is now frequently referred to as one of a series of disruptive technologies that are changing the way we design products and set up new businesses. 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. The amount of time to fabricate models using AM, however, is relatively insensitive to simple design changes that may be implemented during this formative stage of 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 of course 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 multistage processes. With the addition of some supporting technologies like silicone–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.

1.6 Distinction Between AM and Conventional Manufacturing Processes

As mentioned in the discussion on Automated Fabrication, AM shares some of its DNA with conventional manufacturing technologies like Computer Numerical Controlled (CNC) machining. CNC technologies in general are computer-based manufacturing technologies. Conventional technologies are often divided into subtractive, casting, and forming technologies. All can use CNC controllers to increase the accuracy and better control the process. In subtractive manufacturing, such as CNC machining, materials are removed by contact with cutting tools, and therefore chips are produced. In forming the forming tool changes the shape of sheet or blocks of material by exerting high forces, and chips are not generated. In casting, molten material is directed into a mold. CNC machining is capable of making complex parts directly from CAD data but in a subtractive rather than additive way. CNC machining requires a block of material that must be at least as big as the part that is to be made. In AM powders, filaments, liquids, or other feedstocks are added together to create a part that is larger than the feedstock in one or more dimensions.

This section discusses a range of topics where comparisons between CNC machining and AM are made. The purpose is not to influence choice of one technology over another but rather to establish how they may be implemented for different stages in the product development process or for different types of product.

1.6.1 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 fiberboard (MDF), machineable foams, machineable waxes, and even some polymers. However, use of CNC to shape softer materials is typically 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.

1.6.2 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 with 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, even 5-axis high-speed machining, this same process may take weeks for high complexity parts, with considerably more uncertainty over the completion time. This is due to the complex planning involved and custom jigs and fixtures needed to make the part the first time. For the second and subsequent parts, however, CNC machining may be faster than AM.

1.6.3 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 may be 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 and/or joining 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.

1.6.4 Accuracy

AM machines generally operate with a resolution of a few tens of microns. It is common for AM machines to also have different 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 resolution of 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, stereolithography 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 desired geometry and properties of the build material.

1.6.5 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 interpolated 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. 1.3. Many of them would be very difficult to machine without manipulation of the part at various stages.

1.6.6 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 minimized when using preconfigured process parameter combinations. The worst that is likely to happen in most AM machines is that the part will not be built very well if the programming and process parameter selection is not done properly. Incorrect programming of a CNC machine could result in severe damage to the machine and may even be a human safety risk.

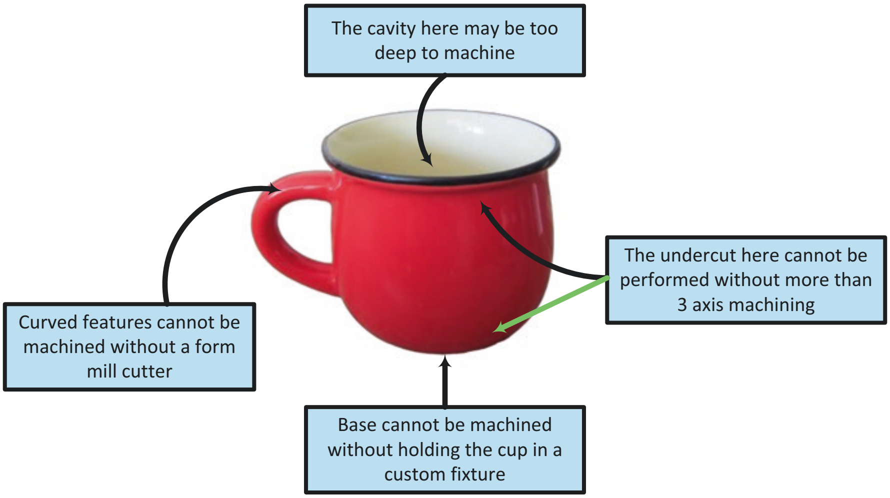

Fig. 1.3 Features that represent problems using CNC machining

1.7 Example AM Parts

Figure 1.4 shows a montage of parts fabricated using some of the common AM processes. Part a. was fabricated using a stereolithography machine and depicts a simplified fuselage for an unmanned aerial vehicle where the skin is reinforced with a conformal lattice structure (see Chap. 4 for more information about the process). A more complete description of this part is included in the Design for Additive Manufacturing chapter. Parts b. and c. were fabricated using material jetting (Chap. 7). Part b. demonstrates the capability of depositing multiple materials simultaneously, where one set of nozzles deposited the clear material, while another set deposited the black material for the lines and the Objet name. Part c. is a section of chain. Both parts b. and c. have working revolute joints that were fabricated using clearances for the joints and dissolvable support structures. Part d. is a metal part that was fabricated in a metal Powder Bed Fusion (PBF) machine using an electron beam as its energy source (Chap. 5). The part is a model of a facial implant. Part e. was fabricated in an Mcor Technologies Sheet Lamination machine that has inkjet printing capability for the multiple colors (Chap. 9). Parts f. and g. were fabricated using Material Extrusion (MEX) (Chap. 6). Part f. is a ratchet mechanism that was fabricated in a single build in an industrial machine. Again, the working mechanism is achieved through proper joint designs and dissolvable support structures. Part g. was fabricated in a low-cost, MEX machine (that one of the authors has at home). Parts h. and i. were fabricated using polymer PBF. Part h. is the well-known “brain gear” model of a three-dimensional gear train. When one gear is rotated, all other gears rotate as well. Since parts fabricated in polymer PBF do not need supports, working revolute and gear joints can be created by managing clearances and remov-

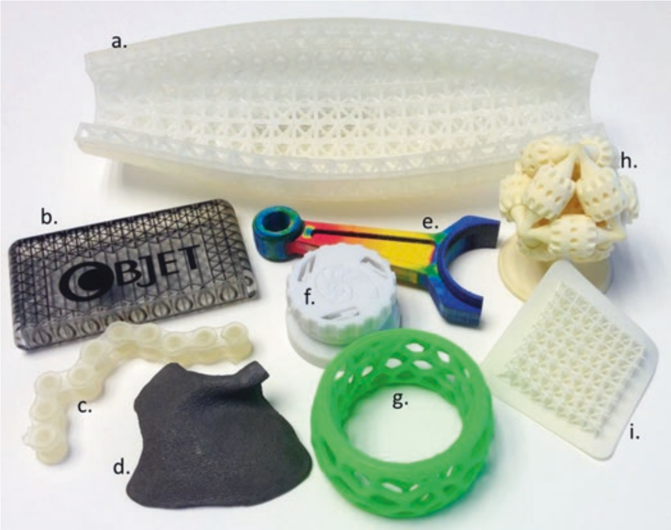

Fig. 1.4 Montage of AM parts

ing the loose powder from the joint regions. Part i. is another conformal lattice structure showing the shape complexity capability of AM technologies.

1.8 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.

1.8.1 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. These data are 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 [8], 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. Recently there have been huge improvements in scanning technology. An adapted smartphone using its in-built camera can now produce a high-quality 3D scan for just a few hundred dollars that even just a few years ago would have required an expensive laser scanning or stereoscopic camera system costing $100,000 or more.

Engineered objects would normally be scanned using laser scanning or touch probe 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 μm. Another approach that can help digitize objects is the Capture Geometry Inside [9] 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 are combined with an engineering design to form a customized medical implant. This is something that will be discussed in more detail later in this book.

1.8.2 Computer-Aided Engineering/Technologies (CAX)

CAX is the use of computer technologies to aid in the design, analysis, and manufacture of products. Computer-Aided Engineering (CAE) is the wide usage of computer software to help engineers analyze their tasks using simulation. Other major CAX sub-categories include Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM).

1.8.2.1 Computer-Aided Design (CAD)

CAD is the use of a computer to aid in the creation, design, modification, analysis, and optimization of a component. CAD software helps increase the efficiency and quality of the design process and enhances communication through documentation by generating organized databases. One of the features of most CAD software is an ability to create electronic output files for printing, machining, or other manufacturing operations. CT images can be converted to CAD files using various software packages, and subsequent modifications can be performed. For instance, to fill the worn part of a bone in the spinal column, CT scan images can be converted to 3D images, and the worn part can be modified and filled. Then in the next step, the file can be saved as an STL file and sent directly to an AM machine for printing.

3D CAD is an extremely valuable resource for product design and development. One major benefit to using software-based design is the ability to implement changes easily and cheaply. If we are able to keep the design primarily in a software format for a larger proportion of the product development cycle, we can ensure that any design changes are performed virtually on the software description rather than physically on the product itself. The more we know about how the product is going to perform before it is built, the more effective that product is going to be. This is also the most cost-effective way to deal with product development. If problems are only noticed after parts are physically manufactured, this can be very costly. 3D CAD can make use of AM to help visualize and perform basic tests on candidate designs prior to full-scale commitment to manufacturing. However, the more complex and performance-related the design, the less likely we are to gain sufficient insight using these methods.

3D CAD is commonly linked to other software packages, often using techniques like the Finite Element Method (FEM) to calculate the mechanical response of a design to certain stimuli, collectively known as Computer-Aided Engineering (CAE). Forces, dynamics, stresses, flow, heat, and other responses can be predicted to determine how well a design will perform under certain conditions. While such software cannot easily predict the exact behavior of a part, for analysis of critical parts, a combination of CAE, backed up with AM-based experimental analysis, may be a useful solution. Further, with the advent of Direct Digital Manufacture, where AM can be used to directly produce final products, there is an increasing need for CAE tools to evaluate how these parts would perform prior to AM so that we can build these products right the first time.

1.8.3 Haptic-Based CAD

3D CAD systems are generally built on the principle that models are constructed from basic geometric shapes that are then combined in different ways to make more complex forms. This works very well for the engineered products we are familiar with but may not be so effective for more unusual designs. Many consumer products are developed from ideas generated by artists and designers rather than engineers. We also note that AM has provided a mechanism for greater freedom of expression. AM is in fact now becoming a popular tool for artists and sculptors, like, for example, Bathsheba Grossman [10] who takes advantage of the geometric freedom to create visually exciting sculptures (including the one shown on the cover of this book). One problem we face today is that some computer-based design tools constrain or restrict creative processes and there is scope for a CAD system that provides greater freedom. Haptic-based CAD modeling systems like the experimental system shown in Fig. 1.5 [11] work in a similar way to commercially available freeform [12] modeling systems to provide a design environment that is more intuitive than standard CAD systems. In this image a robotic haptic feedback device called the Phantom provides force feedback relating to the virtual modeling environment. An object can be seen on screen but also felt in 3D space using the Phantom. The modeling environment includes what is known as Virtual Clay that deforms under force applied using the haptic cursor. This provides a mechanism for direct interaction with the modeling material, much like how a sculptor interacts with actual clay. The results using this system are generally much more organic and freeform than the surfaces that can be incorporated into product designs by using traditional engineering CAD tools. As consumers become more demanding and discerning, we can see that CAD tools for non-engineers like designers, sculptors, and even members of the general public are likely to become much more commonplace.

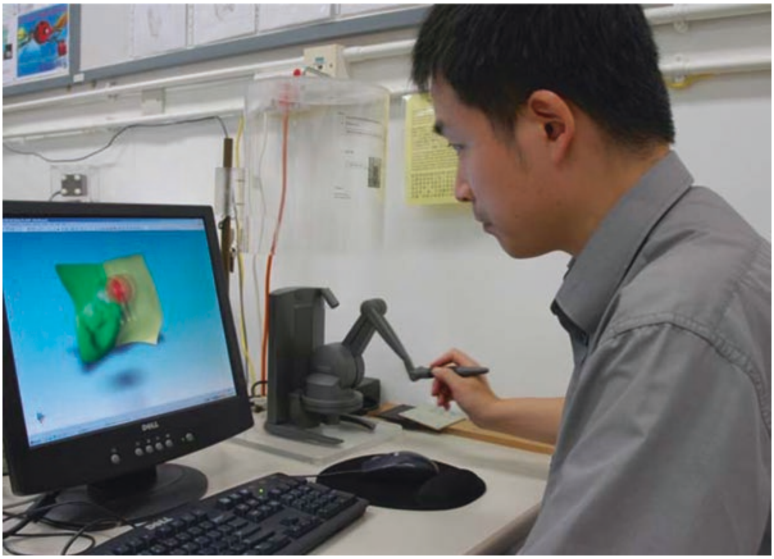

Fig. 1.5 Freeform modeling system

1.8.3.1 Computer-Aided Manufacturing (CAM)

CAM is the use of a computer to control machine tools in order to fabricate a component. The initial purpose of CAM was increasing the speed of manufacturing processes and simultaneously increasing the accuracy, consistency, and precision of manufacturing combined with a reduction of lead time and energy.

The first CAM systems used an individual programmer to create and develop a solution by code writing and manually changing controller options. After significant trial and error, a successful "recipe" would be developed that could be used repeatedly to create identical components. Initial systems were numerically controlled (NC), and the codes were fed into a machine using punch cards. The programs in the NC machine could not be stored and had less flexibility, accuracy, and productivity and also required an expert programmer. The next generation was Computer Numerical Controlled (CNC), where a computer directly controlled the motion of the tool. The programs were fed into the machine directly from computers. In CNC, modification of the programs were greatly simplified. Today, the connection between CAD and CAM is simple and efficient in many software tools.

1.8.3.2 Computer-Aided Engineering (CAE)

CAE is the use of a computer to simulate the effects of various physics applied to a component or system. Today's multi-physics simulation tools are powerful complements to AM. Topology optimization and generative design are commonly used by designers to guide them to a part shape which is the lowest weight component capable of achieving a certain task. AM process simulation tools are a relatively new set of CAE tools, introduced into the market over the past few years. These AM process simulation tools can predict distortion, microstructure, porosity, and other characteristics of an AM part prior to its creation. By simulating the effects of an AM process on a specific geometry, build failures can be reduced, and shape changes that occur in the part can be compensated for prior to production, so that the part can be produced to a higher tolerance and with a higher probability of success [13].

1.9 About This Book

There have been a number of texts describing additive manufacturing processes, either as dedicated books or as sections in other books. Prior to the first edition of this book, however, there were no texts dedicated to presenting this technology in a comprehensive way within a university setting. Universities are incorporating additive manufacturing into various curricula. This has varied from segments of single modules to complete postgraduate courses. This text is aimed at supporting these curricula with a comprehensive coverage of as many aspects of this technology as possible. The authors of this text have all been involved in setting up programs in their home universities and have written this book because they feel that there were no books that covered the required material in sufficient breadth and depth. Furthermore, with the increasing interest in Additive Manufacturing and 3D Printing, we believe that this text can also provide a comprehensive understanding of the technologies involved. Despite increased popularity, it is clear that there is a significant lack of basic understanding by many of the breadth that AM has to offer.

Early chapters in this book discuss general aspects of AM, followed by chapters which focus on specific AM technologies. The final chapters focus more on generic processes and applications. It is anticipated that the reader will be familiar with 3D solid modeling CAD technology and have at least a small amount of knowledge about product design, development, and manufacturing. The majority of readers would be expected to have an engineering or design background, more specifically product design, or mechanical, materials, or manufacturing engineering. Since AM technology also involves significant electronic and information technology components, readers with a background in computer applications and mechatronics may also find this text beneficial.

This third edition has been comprehensively overhauled in an attempt to bring it up to date with the extremely fast-moving landscape of AM. All references have been checked and updated, with many more web-based sources. All images have been checked, with many diagrams redrawn for greater clarity. Replacement photographs show more recent technologies where appropriate. There is much more detail regarding processes and, in particular, on materials. A new chapter on AM materials helps readers understand how new materials are being developed. In particular, there is increasing focus on high performance materials, including ceramics and multi-phase, multi-material structures. We have included as many of these new concepts as we could to show how this exciting domain continues to develop. Finally, we recognize that many educators are including this book as a core text. To help, we have revamped the end of chapter questions as part of a larger process aimed at helping with curriculum development.

1.10 Questions

1. Find three other definitions for Rapid Prototyping other than that of Additive Manufacturing as covered by this book.
2. From the web, find different examples of applications of AM that illustrate their use for “Form,” “Fit,” and “Function.”
3. What functions can be carried out on point cloud data using reverse engineering software? How do these tools differ from conventional 3D CAD software?
4. What is your favorite term (AM, Freeform Fabrication, RP, etc.) for describing this technology and why?
5. Create a web link list of videos showing operation of different AM technologies and representative process chains.

6. Make a list of different characteristics of AM technologies as a means to compare with CNC machining. Under what circumstances does AM have the advantage and under what would CNC?
7. How does the Phantom desktop haptic device work and why might it be more useful for creating freeform models than conventional 3D CAD?
8. With a basic understanding of Additive Manufacturing, what is an application you can think of where additive manufacturing could be used in your daily life? Explain how.
9. What are the differences between end-use parts and prototypes?
10. What was Additive Manufacturing initially used for, and how is it utilized today?
11. Why is the term “Rapid Prototyping” not suitable for additive manufacturing anymore?
12. What is “concurrent engineering”? How can Additive Manufacturing help with concurrent engineering?
13. What type of file is typically required to use as input to process a part in an AM machine?
14. List one academic institution with research activities in AM and some of their research projects that interest you.
15. List one company which produces Additive Manufacturing machines and associated products such as materials and also list one of their products.
16. A company manufactures missile casings with internal channels. Why might Additive Manufacturing be a better manufacturing process than CNC machining?
17. Why have 3D printers not been widely applied for household use today? What benefits do you think AM will bring to your daily life in the future?
18. Visualize a process in which small robots dispersed materials in various places to construct a component. Is this an additive manufacturing process?
19. Recently historical museums have started using additive manufacturing and reverse engineering techniques. What are museums using them for?
20. Why does NASA wish to create an AM lab in outer space?
21. What changes are additive manufacturing making to the mechanical engineering field?
22. Design a product that is very difficult to make using traditional manufacturing methods but that can be printed using AM.
23. Find one Additive Manufacturing application example not covered in this book. List the benefits and disadvantages of this application compared with its traditional manufacturing method.
24. Find the newest definition for Additive Manufacturing by the ASTM F42 Committee. Make a table of all the categories of AM technologies covered in the latest standard and list one typical technique for each category.
25. Discuss how AM can improve manufacturing environmental impact and sustainability.

References

1. ASTM International (2012). Standard terminology for additive manufacturing technologies (F42 on Additive Manufacturing Technologies. Subcommittee F42. 91 on Terminology). ASTM International.
2. Burns, M. (1993). *Automated fabrication: improving productivity in manufacturing*.
3. Wohlers, T. (2009). Wohlers report. State of The Industry: Annual worldwide progress report. Wohlers Associates.
4. ASTM International (2015). *ISO/ASTM52900–15, standard terminology for additive manufacturing – general principles – terminology*. West Conshohocken: ASTM International.
5. Jacobs, P. F. (1995). *Stereolithography and other RP&M technologies: from rapid prototyping to rapid tooling*. Dearborn: Society of Manufacturing Engineers.
6. 3D Systems. (2020). http://www.3dsystems.com
7. Sachs, E., et al. (1992). Three dimensional printing: Rapid tooling and prototypes directly from a CAD model. *Journal of Engineering for Industry, 114*(4), 481–488.
8. Geomagic Reverse Engineering software. (2020). www.geomagic.com/
9. Capture geometry inside. (2020). https://www.moldmakingtechnology.com/suppliers/cgicap
10. Bathesheba Grossman. (2020). http://www.bathsheba.com
11. Gao, Z., & Gibson, I. (2007). A 6-DOF haptic interface and its applications in CAD. *International Journal of Computer Applications in Technology, 30*(3), 163–170.
12. Sensable, 3D Systems. (2020). http://www.sensable.com
13. Goehrke, S. (2020). *Additive Manufacturing Simulation Smartens Up In Latest ANSYS Software Release,* https://www.forbes.com/sites/sarahgoehrke/2019/01/29/additive-manufacturing-simulation-smartens-up-in-latest-ansys-software-release/#1f32adad74eb