State-of-the-Art Survey of Additive Manufacturing Technologies, Methods, and Materials

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State-of-the-Art Survey of Additive Manufacturing Technologies, Methods, and Materials

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Chapter 0: Introduction

The rapid pace of development in additive manufacturing (AM) technology, as well as its interdisciplinary and international nature, makes it an extremely difficult subject to present clearly, concisely, and completely. Daily, more progress is being made toward the maturation of the technology and new applications are being found to utilize it. The purpose of this treatise is not to present a rundown of the "latest developments" in AM; it is a serious attempt to survey and present the mechanics, rationale, basic theory, purpose, practical applications, and limitations of additive manufacturing in the context of engineering and science. The mission of this project is to answer the question "what exactly *is* additive manufacturing?"

In order to answer this, it is essential to look past the media celebration and "cool, revolutionary technology" label. These days it is common to see news items and articles in technical magazines praising 3D printing and AM as the "3rd Industrial Revolution" or a "miracle technology" that is going to solve all of the world's problems; are these claims true or simple media hype? To find out just how well-developed and the technology really is and to provide a basis for future research, a very extensive literature review will be performed and the results will be summarized and organized into this paper. The best available references will be utilized, particularly peer-reviewed journal articles, original process patents, industry standards, recent technical conference proceedings, and books written by well-respected authorities on the subject.

The general progression of this analysis will be:

- Overview and History: The overview and brief history will introduce the basic concept, explain the theoretical "process", and give a background on the technology.
- Basic Processes: This chapter will examine the essential additive processes and a few special processes that the author and advisors found particularly interesting or useful; the processes will be described in detail (when possible referencing the original patent literature), along with some of the machines and materials.
- Applications: This will examine some of the many ways the technology could be used, from basic rapid prototyping to special hybrid manufacturing technologies.
- Economic Sectors: In this section, many possible "users" of the technology will be identified and discussed, including the aerospace and medical industries, archaeologists, educators, electronic manufacturers, artists, and many others.
- Limitations: While the technology holds a lot of promise for the future, there are certainly problems and limitations; these will be discussed in several sections.
- Sustainability and Hazards: This is an aspect of the AM technology that does not often make the headlines; the long-term sustainability, resource use, and possible industrial hazards of AM will be explored.
- Legal and Ethical Concerns: Any advanced technology has the potential for both good use and abuse. This will be discussed in terms of both legality and ethics.
- Economics: This chapter will explore the financial advantages and disadvantages of additive manufacturing, which can depend heavily on the process and material selected for a particular application.

- Future Research: Research that will be needed in the future for the technology to continue to grow and develop will be identified and discussed.

This multi-angled view of the technology, from the basic mechanics to the ways it can be used to improve a company's bottom line to its environmental impacts will make possible an honest and realistic evaluation of the technology and its potential impacts on manufacturing technology.

Chapter 1: Overview and Brief History of the Technology

By definition, additive manufacturing (AM) is the layered fabrication of 3-D solid objects directly from Computer-Aided-Design (CAD) models without the aid of part-dependent tools. It is known by many names, including rapid prototyping, additive layer manufacturing, digital fabrication, direct manufacturing, on-demand manufacturing, desktop manufacturing, freeform fabrication, and freeform manufacturing (Gebhardt, 2012, pg. 2-4; Campbell et al, 2012; Holshouser et al, 2013). Manufacturing in general is defined as the "application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products" (Groover, 2008, pg 23). This is accomplished using a combination of machinery, tools, technical expertise, manual labor, and industry standards. Manufacturing also includes post-processing operations (such as squaring, polishing or painting) and the processes of joining the various parts together to build assemblies. It is usually accomplished in a sequential series of operations. Theoretically, each operation moves the work closer to its intended final state and increases its economic value. In general, the term "manufacturing" refers to subtractive processes, such as milling, sawing, and turning (Black & Kohser, 2008, pg. 6-10).

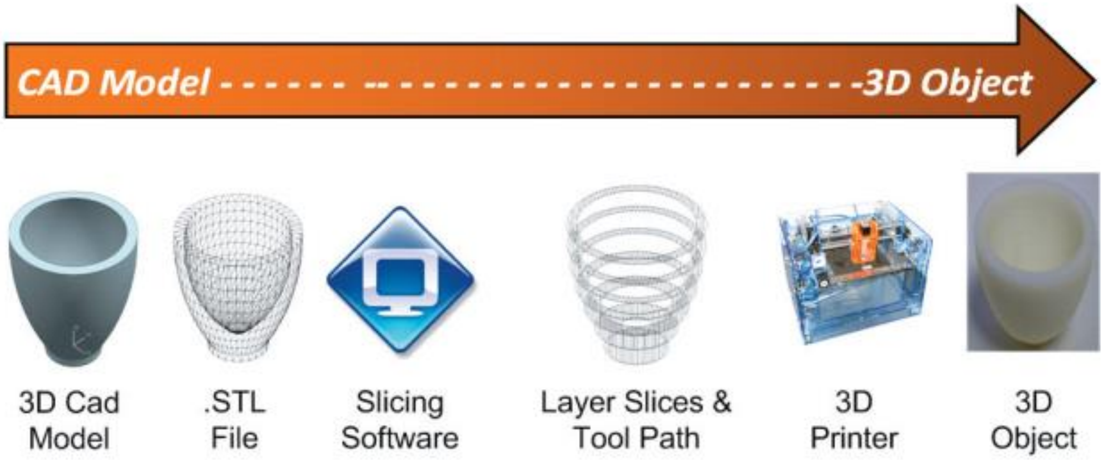

Figure 1.1.1: Basic Concept of AM
Black, 2013

Fabrication of products using AM is directed from a CAD model, usually in the form of a .STL file (ASTM, 2012). The required pre-processing includes orienting the part for printing, designing a support structure (if needed), and generating a "slice" file for the CAD model. The slices are cross-sections of the work piece that have a uniform thickness, allowing the building of the part in layers. The process is done in two steps: layering and fusing. Layering is the creation of a thin layer of material (i.e. a slice), laid out in the desired cross section (including a slice of any required support structure) (ASTM, 2012; Wong & Hernandez, 2012; Huang et al, 2013; Strano et al, 2013). This new layer could be resin, liquid plastic, laminate material, paper, powder-binder matrix, powdered ceramic, food, powdered plastic, or powdered metals, such as stainless steel, titanium, and aluminum (Campbell et al, 2012; Dadbakhsh et al, 2012; Kruth et al, 2007; Guo & Leu, 2013). An energy source, such as a UV light, a laser beam, electron beam, welder, or other heat source is used to provide concentrated energy to the slice of material; this input of energy fuses the recently deposited slice with the layer below. The basic concept is shown in ***Figure 1.1.1***.

Numerous benefits are derived from utilizing this technology, including new and more complicated product design features, integration of functions, lower cost for creating parts due to fewer operations, a simplified supply chain to bring raw material to the machine, reducing the time needed to innovate and launch new product ideas, the elimination of hard tooling, the ability of the technology to produce parts for obsolete or legacy systems, overall lower energy requirements, and more efficient, environmentally friendly manufacturing, and the promise of easy mass customization in manufacturing (Campbell et al, 2012; Bogue, 2013; Petrovic et al, 2011; NIST, 2013; Becker et al, 2005; Diegel et al, 2010; Eyers & Dotchev, 2010). Despite the many benefits offered, AM faces some real challenges. These include a reputation as a prototyping-only technology, limited material selection, software issues, high machine and material costs, product size limitations, issues with material homogeneity and surface finish, the process sensitivity to small modifications in the material and position of material layers, concerns about the strength and final quality of the printed parts, questionable geometric tolerances, and relatively slow print speed (Petrovic et al, 2011; Mahamood et al, 2014; NIST, 2013; Berman, 2012; Pyka et al, 2012; Lappo et al, 2002; Brajlih et al, 2010).

The idea of building solid parts in thin layers began in the 1890's but was not particularly feasible until the invention of inkjet printing in the 1970's, as each layer had to be manufactured as a separate piece before being welded or glued together manually to build the final part (Bourell et al, 2009). Engineer and future co-founder of 3D Systems Charles Hull filed a patent for the stereolithography processes in 1984 (awarded 1986), introducing the world to the concept of rapid prototyping (Hull, 1986; Bourell et al, 2009; Bogue, 2013). By the end of the decade, MIT and Z-Corp had filed a patent (1989) for the 3-dimensional printing (3DP) process (awarded 1993) (Sachs et al, 1993; Butscher et al, 2012), fused deposition modeling was invented by S.S. Crump at Stratasys (patent awarded 1992) (Crump, 1992), and selective laser sintering was under development at the University of Texas – Austin (Deckard et al, 1992; Sun et al, 1989).

The 1990's brought the commercialization of several basic coating processes that would later be used for additive manufacturing, such as cold gas dynamic spraying, friction surfacing, and laser cladding (which would eventually become known as laser powder deposition or LENS) (Alkhimov et al, 1994; Gandra et al, 2013; Koch & Mazumder, 2000). The first commercial stereolithography (SLA) machine to do 3-D printing layer-by-layer was introduced by 3D Systems in 1992 (Bourell et al, 2009; Bogue, 2013). The laminated object manufacturing system was developed by Helisys in the late 1990's to create fast and cheap prototypes out of common materials, such as paper and glue (Feygin et al, 1998). Material jetting was developed by Objet (Israel) in the very late 1990's (US patent not awarded until 2005) with an eye on making cheap, fast, and good polymer prototypes (Gothait, 2005). The various powder bed fusion processes came into commercialization in the 1990's with the introduction of the selective laser sintering process (Deckard et al, 1992). Within a few years, selective laser melting was invented to create full-strength parts that had better properties than those offered by selective laser sintering (Meiners et al, 2001). The 1990's saw the wide adoption of rapid prototyping and the first attempts to apply the technology to manufacturing (Wohlers & Gornet, 2011).

As the technology increased in sophistication into the 2000's, new processes were developed for specialized applications and new variations of existing processes were discovered. New processes that were developed during this time included aerosol jet printing, electron beam melting, bioplotting and contour crafting (King & Ramahi, 2009; Ackelid, 2010; Khoshevis, 2004; Wohlers & Gornet, 2011). Variations of old processes include ultrasonic consolidation, ice plotting, and hybrid layer manufacturing (White, 2003; Liou, 2008, pg. 254-256; Karunakaran et al, 2004), among others. These processes and process variations, as well as regular improvements to the processes developed in the 1980's and 1990's, allowed for mass customization, the ability to manufacture metal industrial parts, the ability to print in several materials, and the ability to print full-strength titanium parts with the EBM process (Edwards et al, 2013; Wohlers & Gornet, 2011).

The technology developed quickly during this time, with continuous improvements to processes and materials. Many new applications were found, including direct manufacturing using additive processes. In 2009, the first industry standards committee was established for additive manufacturing, with the ASTM F42 committee (Wohlers & Gornet, 2011; ASTM, 2012). In 2007, RepRap introduced its Darwin machine, a 3D printer that could print all of its own parts (Jones et al, 2011). That same year, Shapeways introduced commercial 3D printing services for artists and designers (www.shapeways.com) and Bespoke Innovations (now part of 3D Systems) begin to create customized prosthetic limbs using 3-D printing (www.bespokeinnovations.com). In 2009, the MakerBot company begins selling do-it-yourself 3D printer kits and the Organovo company was able to successfully prints blood vessels (Wohlers & Gornet, 2011; www.organovo.com). 2011 saw the introduction of the first 3D printed aircraft, made by the University of Southhampton (Marks, 2011). In 2011-12, silver and gold jewelry is made using 3D printing by Materialise, as well as medical implants created by researchers in Europe (Ferreira et al, 2012; Petrovic et al, 2011). In 2012, the Objet company merged with Stratasys Ltd, which in turn merged with MakerBot in 2013, creating the world's largest producer of AM equipment, with nearly US $3 billion in total market share (Stratasys).

Chapter 2: Essential Additive Manufacturing Processes

2.1. Introduction

Additive manufacturing (AM) was developed from the principles of layer-based technology and utilizes a number of basic processes to accomplish this, including jetting, deposition, extrusion, powder fusion, lamination, and polymerization. Some important special processes or variations of existing processes are ultrasonic consolidation, contour crafting, cold gas dynamic manufacturing, aerosol jet printing, bioplotting, friction surfacing, and ice prototyping. This chapter will discuss the basic AM processes, the important special processes, the commonly utilized machines, and the materials available.

2.2. Binder Jetting Process

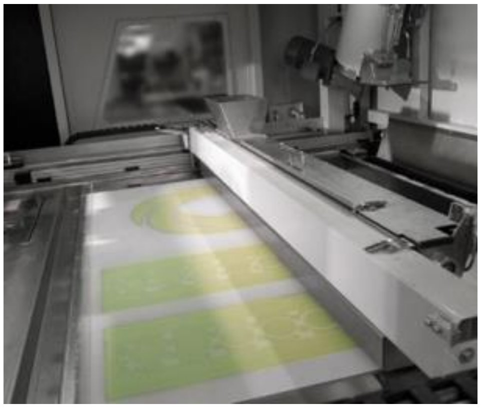

Figure 2.2.1: Binder Jetting Process (3DP)
www.ceramicindustry.com

In the binder jetting process, a liquid binding agent is selectively printed into thin layers of loose powder to join the particles together in a solid layer (ASTM, 2012). Sometimes called 3-dimensional printing (3DP), this process originated from research done at the Massachusetts Institute of Technology (MIT) in the 1980's (Sachs et al, 1993; Campbell et al, 2012). Utilizing a technique similar to standard inkjet printing, the binder material selectively joins the particulate material into a solid form, as shown in ***Figure 2.2.1***. Two powder beds are used; one for the part-in-process and one to store to powder that will be used to create each layer. Two pistons control the operation of the process, one supporting the raw powder bed and the other supporting the part-in-process on a build platform (Gibson et al, 2010, pg. 195; Butscher et al, 2011), as seen in ***Figure 2.2.2***.

As each layer is printed, the build platform lowers the distance of one layer thickness and the powder supply raises the same amount. A roller or wiper then transfers and levels one part-slice worth of powder onto the now empty space on top the build bed; the print head then deposits the binder into the powder in the desired slice geometry pattern. This layer-by-layer process is repeated until the desired 3-D object is completed (Gibson et al, 2010, pg. 195; Moon et al, 2002). Following the completion of the part, it is heat treated in order to cure all the binder and bring the part to full strength. The unbound powder is then removed with compressed air or by vacuum, leaving the final part. Depending on the application, the part may be used in its current state or subjected to infiltration or sintering to give it specific properties (Khalyfa et al, 2007; Lee et al, 2006; Lappo et al, 2002). The most common infiltration materials are wax, metals, and epoxy resin (Butscher et al, 2011 & 2012; Campbell et al, 2012).

There are many advantages to employing this process including simplicity, flexibility, and the ability to print several colors or materials into one part, as seen in ***Figure 2.2.3***. This is one of the fastest and most flexible AM processes (Huang et al, 2013; Hackney, 2003). The support gained from the powder bed allows overhangs, undercuts and hollow spaces to be created easily, as long as there is a hole so that the unbound powder can be cleaned out of the part after printing (Becker et al, 2009; Adam et al, 2014). It can create objects out of essentially any material that can be obtained as a powder, including metals, ceramics, silicates, food, plastics, and bone material (Sereno et al, 2012; Williams et al, 2011; Castilho et al, 2013; Bose et al, 2013). The process works at room temperature and does not require shielding gas or heated build chambers, eliminating some of

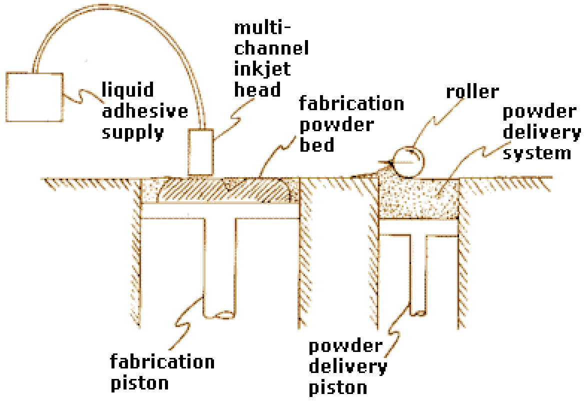

Figure 2.2.2: Binder Jetting Process (3DP)
www.efunda.com

the challenges and disadvantages of some of the other additive processes, such as layer shrinkage (Vaezi & Chua, 2011; Moon et al, 2002).

In spite of the many advantages to using a binder jetting process, challenges remain. The final quality of the created parts is dependent on the quality of the powdered material, the quality of the binder material, and the quality of the post-processing used (Guo & Leu, 2013; Vaezi & Chua, 2011). This limits the application range for the parts made by this process. The unprocessed surface quality of parts made is rough and lacks perfect dimensional stability (Ibrahim et al, 2009; Silva et al, 2008; Hackney, 2003), but proper infiltration, sintering, and surfacing can do a lot to remedy this (Butscher et al, 2011; Crane et al, 2006; Bai et al, 2007).

Figure 2.2.3: Example of 3DP Part
http://3d-spot.pl

There are several types of machines available to do binder jet printing. Foremost are the machines made by Z-Corporation in Burlington, Massachusetts, the original licensee from MIT to commercialize the binder jetting process. They are offered in several sizes, from desktop to industrial scale. Variations on the process come from Ex-One LLC's Prometal Division in Irwin Pennsylvania and Voxeljet Technology in Friedberg Germany. The Prometal machines use the binder jet process to create raw metal parts and complex sand shells for casting (Gebhardt, 2012, pg. 47-51; Bassoli et al, 2007). The Voxeljet machines are used mainly for plastic printing applications. The build chambers are large and several parts can be made simultaneously, using different binders and producing different properties. A common application for the Voxeljet machines is the creation of complex and fine masters for casting (Gebhardt, 2012, pg. 47-51).

2.3. Material Jetting Process

The material jetting process selectively deposits droplets of photo-curable build material in a specified pattern, in order to create a slice of the part. The fusion is done by UV light (ASTM, 2012; Gothait, 2005). Also sometimes known as inkjet 3-D printing, Polyjet, and direct write manufacturing, the material jetting process was first commercialized a few years ago, with the introduction of the Polyjet machine. The operation has many similarities to the binder jetting process, except it prints thin layers of liquid material instead of binder and builds on a flat table instead of a powder bed, as can be seen in ***Figure 2.3.1***. In the binder jetting process, one or several jets dispensed binder into the powder bed; in the material jetting process, several rows of tiny jets dispense the photopolymeric material. The build is done at room temperature and does not require any special shielding agents or a vacuum to operate (Gibson et al, 2010, pg. 171-173 & 259).

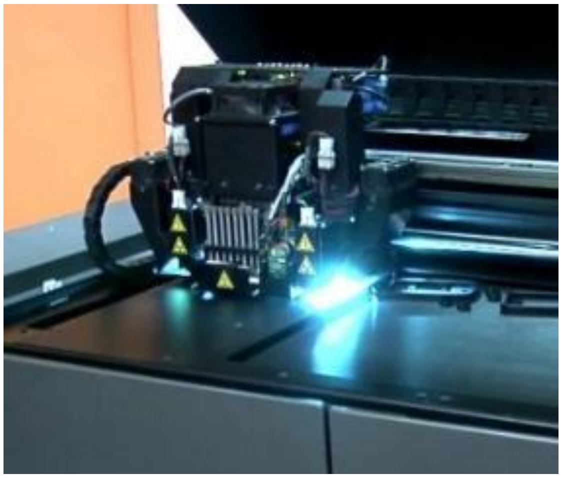

Figure 2.3.1: Material Jetting Process (Polyjet)
www.3dnatives.com

Curing is done instantaneously with pair of UV lights or other energy source, which cures and bind each layer of photopolymer together as the part is built, as shown in ***Figure 2.3.2***. As each layer is printed inkjet-style and cured the build table lowers the distance of one part slice, allowing the next layer to be printed (Fahad et al, 2013; Bogue, 2013). This is a very fast, simple, and clean AM process. The print head deposits just enough of the photopolymer to manufacture the part and its support material, conserving space and material. However, since there is no powder bed to offer support during part construction, supports must be printed where required, usually of a different and softer material than the part (Gebhardt, 2012, pg. 37; Fahad et al, 2013). While the material jetting process is typically done at room temperature, some research has been done on the effect of heating the material to make it flow better (Fathi et al, 2012). Some research has also been done to extend the mechanics of the process to print molten metal (Muller et al, 2014).

The major advantages of utilizing this process are its speed, extremely fine detail (***Figure 2.3.3***), relatively inexpensive raw material, and its ability to create parts that do not need any post-processing, other than a basic cleaning and removal of support materials, and its ability to create multiple-material parts (Ibrahim et al, 2009; Gibson et al, 2010, pg. 174; Guo & Leu, 2013). This process works with a huge array of materials, including rigid opaque photopolymers in an almost unlimited variety of colors, clear and colored transparent ones, rubber-like materials, hydrogel, impregnated resins for ceramics manufacturing, and specially created photopolymers for 3D printing in the dental, medical and consumer products such as dentures and cell phone cases (Billiet et al, 2012; Guo & Leu, 2013; Derby & Reis, 2003). This is one of the best AM processes for finished-product realism, fine detail, and very good surface finish (Vaezi et al, 2013; Fahad et al, 2013); however, parts made with this process are not as strong or durable as some of the other processes, so application should be considered carefully when selecting this process (Wong & Hernandez, 2012).

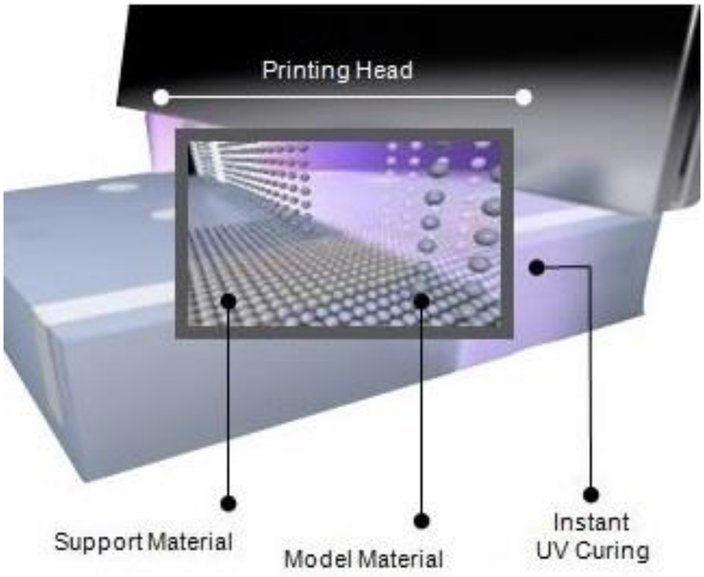

Figure 2.3.2: Material Jetting Process (Polyjet)
www.advtek.com

Figure 2.3.3: Polyjet Part
www.solidconcepts.com

The material jetting process and machines were commercialized by the Objet Geometries Inc. of Rehovat Israel (Gibson et al, 2010, pg. 173), until the company merged with Stratasys Ltd. in December of 2012. The printers are sold under the Objet and Polyjet badges by Stratasys Ltd. of Eden Prairie Minnesota (Stratasys).

2.4. Directed Energy Deposition Processes

This AM process came into being from research done at Sandia National Laboratories in the 1990's with the introduction of the Laser Engineered Net Shaping (LENS) process (Mudge & Wald, 2007; Koch & Mazumder, 2000). The main characteristic of directed energy deposition processes (DEDP) is the simultaneous deposition and fusing of material, usually by means of a thermal energy source like a laser, plasma arc, or electron beam (ASTM, 2012; Gibson et al, 2010, pg. 237; Bi et al, 2012). The raw material can be in the form of powder (***Figure 2.4.1***) or wire feedstock (***Figure 2.4.2***). In theory, the process is good for plastics, polymers, ceramics, and composite materials, but it is mostly used for metal powder-based manufacturing (Gibson et al, 2010, pg. 237-239; Costa & Vilar, 2009; Zhang et al, 2013). The best materials to use with this process are ones that have good weldability, such as steel and stainless steel, but titanium, cobalt, and nickel alloys have been successfully printed with this process. Metals with high thermal conductivities and reflectivities such as gold and aluminum are hard to use, as well as materials that oxidize easily (Gibson et al, 2010, pg. 248).

Figure 2.4.1: LENS/DMD
www.extremetech.com

There are two major types of direct energy deposition processes: powder feeding and wire feeding. The powder system is commonly known as Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD) or laser cladding. It uses a combination of powder jets, mirrors, powder nozzles, and inert gas tubes, as seen in Figure 2.4.3. The process must be done with shielding gasses in a controlled chamber to prevent contamination and allow the process to work correctly (Gibson et al, 2010, pg. 239). The wire feed process is typically known as Wire Freeform Fabrication (F³) (Figure 2.4.4). This print head consists of an extruder for the wire and required energy sources (usually a laser, electron beam, or plasma arc) to melt and fuse the deposited material, as well as jets for shielding gasses (Gibson et al, 2010, pg. 244; Aiyiti et al, 2006; Horii et al, 2008; Wanjara et al, 2007). The result bears strong resemblance to an excellent weld, built layer upon layer (Bi et al, 2012; Dutta et al, 2011).

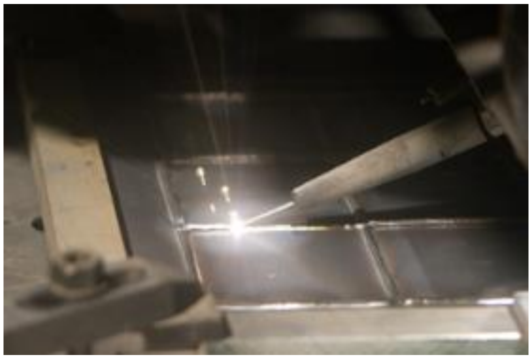

Figure 2.4.2: Wire Freeform Fabrication
www.nasa.gov

The two processes work by depositing the raw material into a molten area on the build surface, either by spraying powder or by extruding wire. The energy source then melts the new material into the melt pool, creating a new layer of material and adding to the mass of the part. When comparing the two processes, the powder deposition gives much finer detail and surface finish and has a wider range of applications. Any powder that is not captured by the melt pool can be collected and recycled later (Gibson et al, 2010, pg. 241; Costa & Vilar, 2009). The wire feed system is

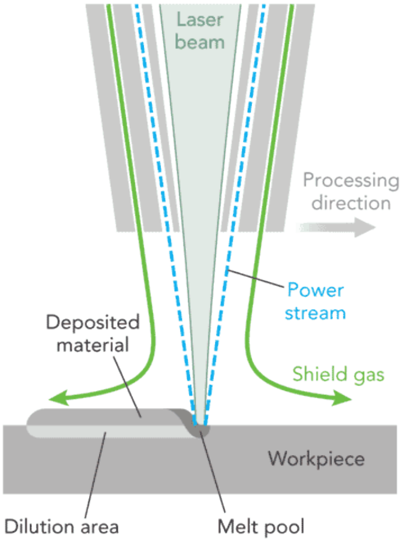

Figure 2.4.3: Powder Feed DEDP
www.industrial-lasers.com

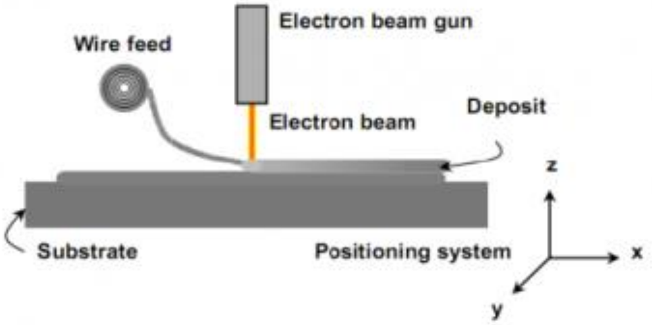

Figure 2.4.4: Wire Feed DEDP
www.whiteclouds.com

best for very large parts, as the process is extremely fast. However, the results can be quite rough if the parameters are not controlled (Gibson et al, 2010, pg. 244). There are various setups of the process that allow the print head to move, the part to move, or some combination of the two; the latter of the three is the most versatile. The print head is usually set on in 3-axis configuration, but robotic-arm-based configurations exist (Gibson et al, 2010, pg. 239; Dutta et al, 2011; Escobar-Palafox et al, 2011). This process causes little to no heat distortion, since the layers are very small. It is a relatively fast and simple process and the raw material is not very expensive (Gu et al, 2009; Dutta et al, 2011).

The major advantage of using directed energy deposition is its ability to build very large parts, as well as make thin-walled components and ones with very fine details due to the small heat region and the full-melting of the material during the process (Mudge & Wald, 2007). It can also be used to repair cracks or wear on large parts (***Figure 2.4.1***), add features to existing parts (***Figure 2.4.2***), and print contoured geometry (***Figure 2.4.1***) (Gibson et al, 2010, pg. 244-248; Mudge & Wald, 2007). This process is sometimes used in parallel with a CNC milling machine in hybrid layer manufacturing (Karunakaran et al, 2009). For both processes, the material is brought to the part under pressure (the powder is blown and the wire is extruded), allowing the deposition and fusing of the layers to be made at any angle, as seen in ***Figure 2.4.5*** (Gibson et al, 2010, pg. 240).

This is a very common process for printing metal parts and there are many commercially produced systems available. The first and most widely used is the original LENS process, marketed by Optomec. There are also processes such as the Directed Light Fabrication (DLF), Direct Metal Deposition (DMD), 3D Laser Cladding (3DLC), Laser-Based Metal Deposition (LBMD), Laser Freeform Fabrication (LFFF), Laser Direct Casting (LDC), and Laser Consolidation (LC) that are commercially available (Gibson et al, 2010, pg. 238).

Figure 2.4.5: Print Head for LENS
www.directindustry.com

2.5. Material Extrusion Process

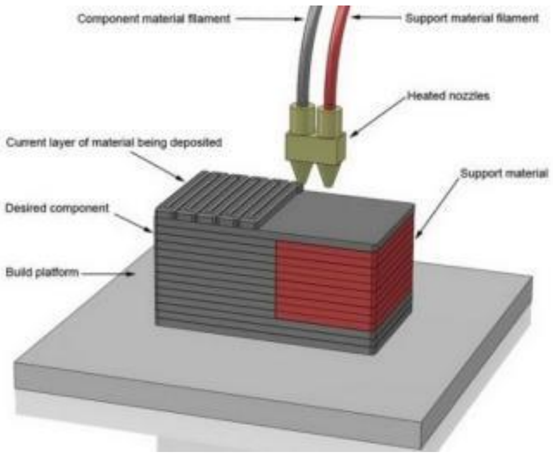

Figure 2.5.1: FDM Process
www.ciri.org.nz

Material extrusion processes are important to both formative and additive manufacturing. In the case of formative manufacturing, this process would be utilized to produce wire or bar stock. In AM, the raw material (and any needed support material) is extruded out of a movable nozzle or other orifice and selectively deposited to create layers of material, as shown in ***Figure 2.5.1*** (ASTM, 2012; Crump, 1992). This process, sometimes known as fused deposition modeling (FDM), was developed in the 1980's and commercialized by Stratasys (Guo & Leu, 2013). The action of the process (***Figure 2.5.2***) can be visualized as a computer-controlled cake-icing operation (Gibson et al, 2010, pg. 143). Fusion between the bead that is extruded and the layer below it is accomplished by keeping the raw material molten in the extruder nozzle and the atmosphere is the build chamber near the melting point of the material, keeping the material nearly fluid (Gibson et al, 2010, pg. 143-144).

This is the most common AM process and the one typically utilized by desktop and hobby 3-D printers to print thermoplastic materials such as ABS, PC, PC-ISO and PPSF (Gibson et al, 2010, pg. 159-160). Usually the raw material is fed into the machine as plastic wire from a roll. Multiple print extrusion nozzles can be used on the print head, allowing the machine to print in several colors or with several materials. Typically a machine will have two nozzles, one for printing the material and one for printing the support material. Due to the operation of this process, support material is required for any overhangs, undercuts, and hollow spaces in the part (Gibson et al, 2010, pg. 160-161).

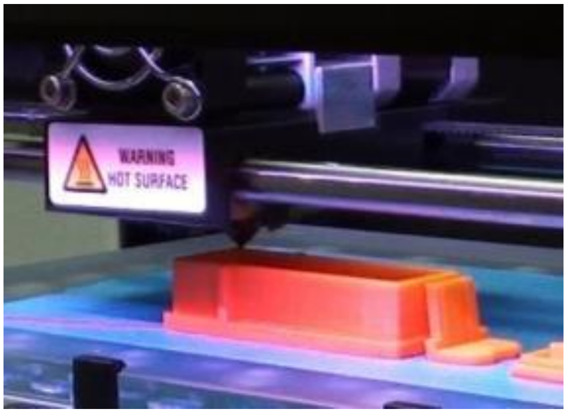

Figure 2.5.2: FDM Process
www.inkfactory.com

There are some problems with utilizing this process, especially in terms of the print speed, the accuracy, the precision of the build, and the material density and surface finish of the final parts. The nozzles in the print head are circular, making it impossible to print sharp corners or edges in a part and restricting the ability to build thin-walled parts (Gibson et al, 2010, pg. 160-161; El-Katatny et al, 2010). The quality of the build, the material density, and the surface finish are heavily dependent upon the print speed, the solidification properties of the material, and the quality of the printer and nozzles (Gibson et al, 2010, pg. 156 & 158-159). ***Figure 2.5.3*** shows a very fine-detailed example of FDM. In spite of the potential problems, there are a number of advantages to using this process, particularly the price and simplicity of the machines, the good material properties of parts, and the low cost of raw material (Guo & Leu, 2013).

Compared with many other 3-D printers, the material extrusion machines are very cost effective. Several variations of cheap, entry-level printers are easily available out the door from office supply stores. Printrbot sells a do-it-yourself 3-D printer kit based on the material extrusion process for about $350 (amazon.com, price on February 18, 2014). Office Depot Inc. offers a simple, single-nozzle printer (3D Systems Cube) off the shelf for $1300, a two-nozzle printer (3D Systems CubeX) for $3000, and a three-nozzle version of the CubeX printer for $4000 (www.officedepot.com, prices on February 18, 2014). There are many, much more expensive, variations however. The best and most expensive FDM machine available is the Stratasys Fortus 900mc, which can make medical-quality parts from 9 different materials or colors of material simultaneously, has a very large build area, builds parts very quickly, and sells for around $750,000 (www.stratasys.com).

Figure 2.5.3: FDM Part
www.cadalyst.com

2.6. Powder Bed Fusion Processes

This process, sometimes known as direct metal laser re-melting (Pogson et al, 2003), employs a source of thermal energy to selectively sinter or melt specific regions of a powder bed in order to create layers of solid material in a specific shape (ASTM, 2012). There are a large number of these processes, but this section will focus on the three most common and well-developed processes. There are selective laser sintering (SLS), selective laser melting (SLM), and electron-beam melting (EBM). In all of these processes, a powder bed provides the required support for the part during construction. The operation of the powder bed during construction is identical with that described in *Section 2.1. Binder Jetting Process* and any left-over powder can be recycled and reused as long as it is clean (Deckard & Beaman, 1987; Simchi, 2006; Dotchev & Yusoff, 2009; Athreya et al, 2013). Powder bed fusion, in theory, can handle any material that can be purchased in powder form and fused by heat. However, it is rarely used for anything except metals and ceramics, with the exception of the SLS process (Gebhardt, 2012, pg. 40). The SLS and SLM processes were invented and developed in the 1990's, while the EBM is a much more recent invention.

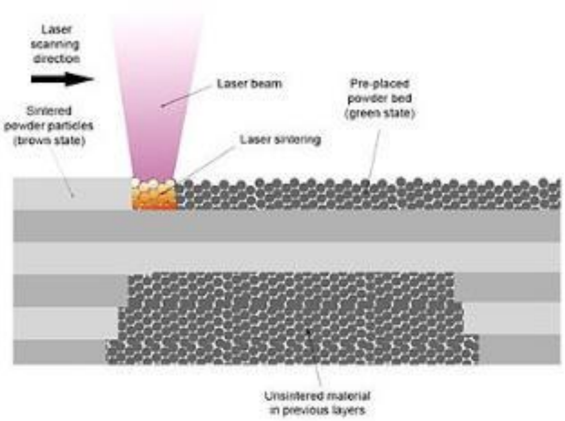

Figure 2.6.1: SLS/SLM Process
en.wikipedia.org

The SLS process, seen in ***Figure 2.6.1***, fuses particulate material into a solid part by causing localized melting of the particles, also known as sintering, using a laser beam as the energy source (Bourell et al, 1994; Deckard et al, 1992). This process is identical to the classic sintering process except it is selective and is accomplished in layers. The particles do not melt completely, but undergo a solid-state diffusion that joins them together (***Figure 2.6.2***). Typically in sintering, the material is heated to 70-90% of the material melting point and all the operations must be done in a vacuum or protected environment to prevent contamination and reduce the porosity of the parts (Black & Kohser, 2008, pg. 468). The properties, density, and surface finish of the parts created are similar to parts produced using a power-metallurgy process and some post-processing is typically required to bring the surface to required specifications (Shahzad et al, 2013). This process is very fast and can create very complex parts; however, the parts are not full-density and do not have the same strength or resilience as machined or cast parts (Gibson et al, 2010, pg. 105-107; Ibrahim et al, 2009; Simchi, 2006). ***Figure 2.6.5*** shows a typical part make with SLS. Infiltration is sometimes used with "green" parts made with SLS, as the material is relatively porous, in order to bring them to full strength; this was common before SLM came into regular use (Lappo et al, 2002; Stevinson et al, 2007). Usual materials that can be sintered easily are hard plastics, aluminum, brass, copper, steel, stainless steel, carbides, tungsten, and ceramics (Black & Kohser, 2008, pg. 469; Drummer et al, 2010; Bertrand et al, 2007; Simchi, 2006; Klocke et al, 2007). Loose powder is typically used, but a binder could be used to give the sintered material specific properties and to make green parts for furnace sintering after the print is finished. This is known as indirect selective laser sintering; the binder is usually burned or melted away as the powder is sintered by the laser (Lappo et al, 2002; Shahzad et al, 2012).

Figure 2.6.2: SLS/SLM
www.makepartsfast.com

Selective laser melting (SLM) works in a similar way to SLS, except that the particles are completely melted (welded) in the process (Meiners et al, 2001; Gibson et al, 2010, pg. 124; Abe et al, 2001). This is accomplished with the same setup as SLS (***Figure 2.6.1***), except that the laser is moved slower and the material heated to the melting point. While SLM is slow and requires a lot of energy to operate, the part properties are far superior to SLS; there is low residual stress in the part (Mercelis & Kruth, 2006), the properties are near those of cast or machined parts, it can create very fine and complex features, and has an excellent surface finish (Gebhardt, 2012, pg. 42; Dadbakhsh et al, 2012). Its ability to create very fine geometry makes it ideal to create parts with lattice and partially-formed structures, resulting in fully-functional components that are much lighter-weight than machined or cast ones (Gu et al, 2012) (***Figure 2.6.5***); this is ideal for medical and aerospace applications. The materials that can be worked using this process are the same as in SLS, with some very hard materials included, such as titanium, steel alloys, nickel alloys, and some ceramics (Gebhardt et al, 2010; Thijs et al, 2010;

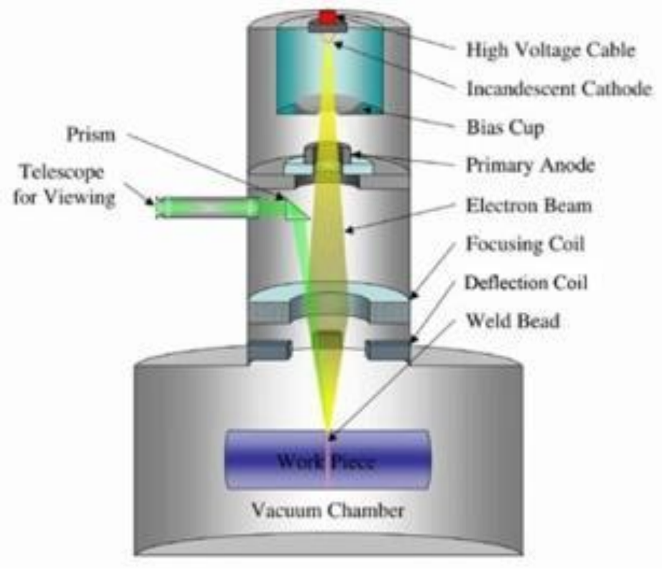

Figure 2.6.3: Electron Beam Melting
www.popular3dprinters.com

Rombouts et al, 2006; Dutta & Froes, 2014; Wilkes et al, 2013).

Of the three major powder bed fusion processes, electron mean melting (EBM) (Ackelid, 2010) provides the best properties, gives a decent surface finish, and has a fast build rate. It is faster than SLS and has slightly better properties than SLM (Gibson et al, 2010, pg. 128-129; Gebhardt, 2012, pg. 44). In this process, the laser in replaced by an electron beam, as seen in ***Figure 2.6.3***, which melts the powder fully and fused it completely with no gaps or voids (***Figure 2.6.4***). It is important to note that this process can only use metal powder, as it must be electrically conductive for EBM to work (Gibson et al, 2010, pg. 128; Ribton, 2012). The parts than come out of this process are full-density, full strength, and can be made with properties superior to those is traditionally-manufactured parts; this is the only AM process currently in use that provides this (Rannar et al, 2007; Reginster et al, 2013). If the build is designed well, the parts can be ready to use right of the machine and do not need and surface treatments or post-processing. The most serious disadvantage to using the EBM process is the cost, both for the machines and to operate and maintain them. While the energy necessary to operate an electron beam is less than that of an equivalent laser system, it is still quite significant as a more powerful beam is required than that required for SLS or SLM (Gibson et al, 2010, pg. 129-130). While the machine is building a part, a near-perfect operating environment must be maintained or the part may be contaminated by impurities. The electron beam process is extremely powerful and fast and is best suited to materials with high melting points (Gebhardt, 2012, pg. 44); it must be monitored frequently to make sure everything is working correctly and that flaws do not form in the parts during manufacture (Dinwiddie et al, 2013; Schwerdtfeger et al, 2012). EBM is mainly used to create full-density and strength titanium parts (***Figure 2.6.5***) since these are so difficult to manufacture traditionally that the high cost of using EBM to manufacture them is justified (Edwards et al, 2013; Dutta et al, 2014).

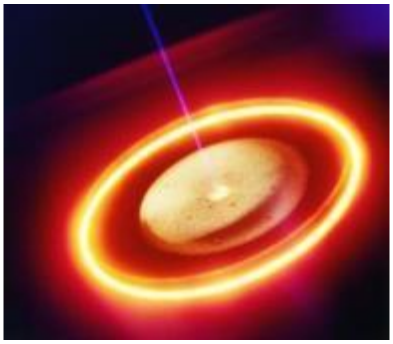

Figure 2.6.4: EBM Process
ir.arcam.se

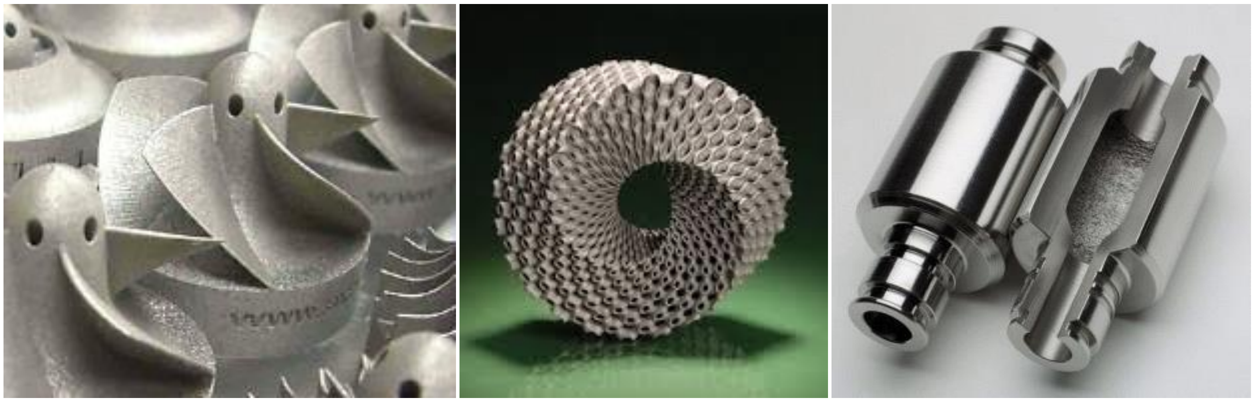

Figure 2.6.5: Typical Parts Made by SLS, SLM, and EBM (Left to Right)
www.mindtribe.com, www.twi-global.com, and www.answers.com

There are a number of manufacturers of powder bed fusion machines. Machines that operate on the SLS process are available from 3D Systems of Rock Hill, South Carolina and EOS-GmbH of

Munich, Germany. Most of the SLM machines available come from Germany and are offered by EOS-GmbH, Realizer-GmbH of Borchen, Concept Laser GmbH of Lichtenfels, and SLM-Solutions of Lubeck. The EBM process is owned and commercialized by Arcam AB of Molndal, Sweden (Gebhardt, 2012, pg. 40-44; Dinwiddie et al, 2013).

2.7. Sheet Lamination Process

Sheets of the raw material are laid out, cut to shape, and bonded together in the sheet lamination process (ASTM, 2012; Feygin et al, 1996). The cutting is done with a laser, blade, or mill and the bonding can be accomplished using adhesives or melting to join the layers of material together (Windsheimer et al, 2007; Luo et al, 2013). The process was developed by Helisys (now Cubic Technologies of Torrance, California) in the 1980’s (Guo & Leu, 2013), making it one of the oldest commercial AM processes. This is one of the most commonly used prototyping processes, due to its speed and very low cost of the material. The process is typically known laminate object manufacturing (LOM) or layer laminate manufacturing (LLM), regardless of the material used (Gebhardt, 2012, pg. 52). ***Figures 2.7.1 and 2.7.2*** show the process in operation.

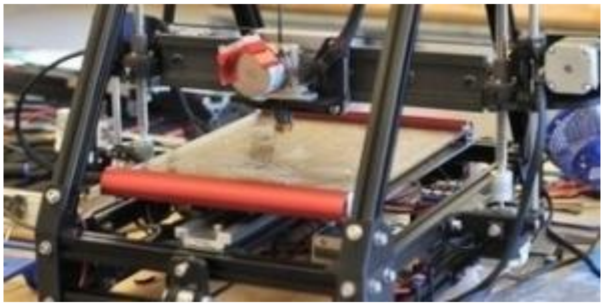

Figure 2.7.1: Desktop LLM Machine in Operation
www.designingwithleds.com

Instead of requiring the raw material to be in the form of powder or molten fluid, LLM uses sheets of the desired material, which could be paper, plastic, vinyl, or metal foil (Deckard & Beaman, 1987; Gebhardt, 2012, pg. 52). An LLM process “prints” the part layers by advancing an adhesive-coated sheet of the material over the build platform, rolling it out on the platform using a heated roller, cutting out the desired slice shape, then lowering the platform the thickness of one layer and repeating the process until the part is finished, as seen in ***Figure 2.7.2***. Any extra material that was not used in the part remains in place to serve as support material until the part is finished; it is cut into small blocks by the laser during the printing and is therefore easy to remove. Some parts will require post-processing such as varnishing or sintering (Gibson et al, 2010, pg. 207-213; Guo & Leu, 2013; Windsheimer et al, 2007).

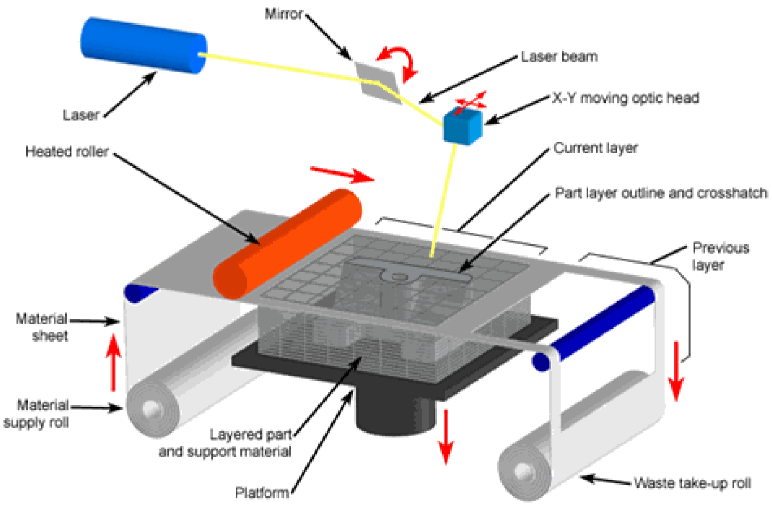

Figure 2.7.2: Sheet Lamination Process (LLM)
www.custompartnet.com

The major advantages of this process are its simplicity, speed, low cost, and ability to manufacture huge and very detailed objects quickly;

prototypes of large gears, tires, and transmission housings are some of the things commonly made (Gebhardt, 2012, pg. 52-55). ***Figure 2.7.3*** shows a very detailed art piece created using LLM. Theoretically, functionally-graded and multiple-material parts can also be created with this process (Oxman, 2011; Vaezi et al, 2013). In spite of the process abilities, there are two disadvantages: the parts are usually only valuable as prototypes and there is a huge amount of waste material left over at the end that cannot be recycled (Gebhardt, 2012, pg. 52).

Figure 2.7.3: Example of LLM Part
www.buy3dprinter.org

This is a common process for rapid prototyping and there are a variety of machines available to do the job, mostly based on rolls of paper and laser cutting. The original machine from Cubic Technologies is no longer produced, but there are still a number of them in use. Mcor Technologies of Ardee, Ireland, offer a LLM machine that uses sheets of standard copier paper and PVA glue, reducing the cost of prototyping even further. Solidimension offers a LLM machine that uses plastic sheets and an epoxy to create reasonably strong and durable plastic parts (Gebhardt, 2012, pg. 52-55).

2.8. Vat Photopolymerization Process

According to the ASTM, vat polymerization is the process where a liquid photopolymer in a vat is selectively cured with a laser (ASTM, 2012). This process is commonly known as stereolithography (SLA) or optical fabrication (***Figure 2.8.1***). Along with material extrusion processes, this is what most people visualize when they use the terms "rapid prototyping" and "3-D printing". Invented and patented in the 1980's by Charles Hull (Hull, 1986), the process is the first and one of the most widely used for rapid prototyping to this day (Huang et al, 2013; Wong & Hernandez, 2012). Recently, stereolithography has been developed to the point where it is able to produce production-quality parts under the right conditions. Of all the AM processes in use, SLA gives the best detail of features and surface finish (Manoharan et al, 2013; Gebhardt, 2012, pg. 34).

The raw material used in the process is a liquid photopolymer that can be solidified and cured using a UV light or laser. The most common materials are epoxy and acrylic resin (Deckard &

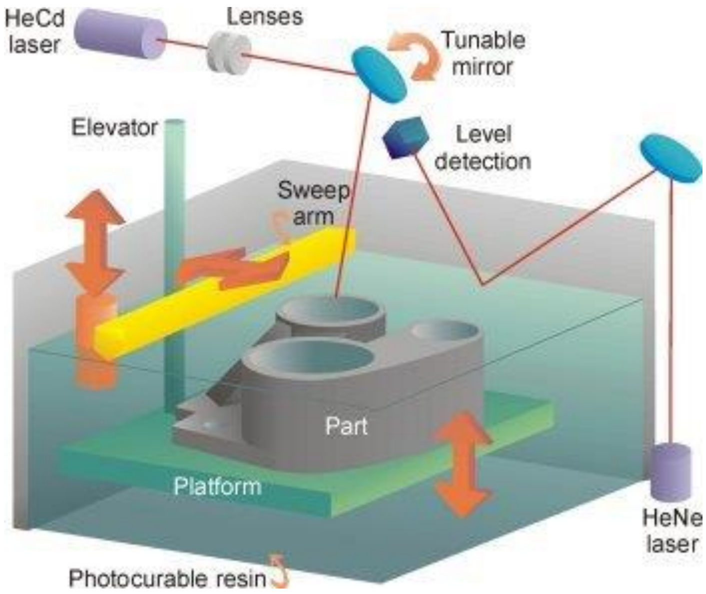

Figure 2.8.1: Vat Polymerization Process (Stereolithography)
www.princeton.edu

Beaman, 1987; Guo & Leu, 2013). The operation is started by the build table submerging the depth of one slice thickness into the vat of liquid. Some variations of the process let the liquid flow naturally over the part and some use a paddle to spread it. The laser or UV light then traces out the cross-section of the part, curing and fusing it. The table then moves down one layer thickness and the liquid photopolymer again covers the top of the part. This process is repeated until the desired product is completed (Gibson et al, 2010, pg. 71-75). SLA can be observed in operation in ***Figure 2.8.2***. Support material is usually required for any hollow areas or overhangs to prevent them from deforming during the build. This material will be removed later as part of the post-processing operation (Huang et al, 2013), which may also include curing, sintering, machining, varnishing, and polishing depending upon the desired application (Gebhardt, 2012, pg. 34-36).

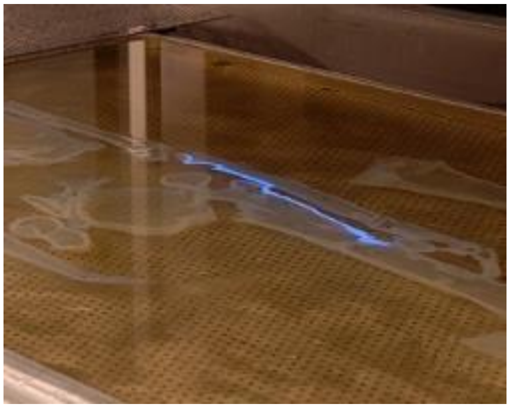

Figure 2.8.2: STL In Process
i.materialise.com

There are several important advantages to utilizing this process, including its build speed and quality, its ability to make very detailed features, and possibility of customizing the properties of the part. SLA can create large parts quickly, up to 2 meters in length in a matter of hours, with very detailed and fine features (Nizam et al, 2006; Petrovic et al, 2011). ***Figure 2.8.3*** shows a typical part created with SLA. It is possible to customize the properties of the material, and even make use of multiple materials, by controlling the build rate, the depth of laser penetration, and the type of photopolymers used (Gibson et al, 2010, pg. 71-72). In spite of the good characteristic of the process, there are three major disadvantages: Parts made by SLA can become brittle and degrade when exposed to UV radiation, normally-made SLA parts are only valuable as prototypes due to relatively poor long-term stability and heat deflection abilities, the range of available materials is low, and the process is rather expensive (Gibson et al, 2010, pg. 71-75; Huang et al, 2013; Zhou et al, 2013).

Recent research has dramatically increased the strength and value of SLA-created parts by introducing various additive materials, including glass, carbon, metals, and nanotubes (Gebhardt, 2012, pg. 36-37). Research has also been done into using SLA to make very tiny parts for electronics and medical applications, due to the extremely fine detail of the features, as well as multiple-material parts (Choi et al, 2010 & 2011; Hieu et al, 2005). The process is also valuable for rapid tooling processes since it creates soft parts that have very detailed features.

SLA machines are available from Materialise, 3D Systems, CMET of Japan, and CP-GmbH of Berghof, Germany. The machines from Materialise create the largest parts, up to 2 meters in length and 0.7 meters wide. A few years ago, a good STL machine could cost up to half a million dollars, but much more cost effective options are on the market now (Gebhardt, 2012, pg. 34-37; Guo & Leu, 2013).

Figure 2.8.3: Typical Part Made With STL
www.3dguys.com

2.9. Special Process - Ultrasonic Consolidation

Although not defined as an AM process by the ASTM F2792-12a standard, ultrasonic consolidation (USC) is a promising and interesting additive process for the manufacture of metal parts. This process has been available since the early 2000's, but is still relatively rare and unknown (Gebhardt, 2012, pg. 55). ***Figure 2.9.1*** shows the basic setup of a USC process.

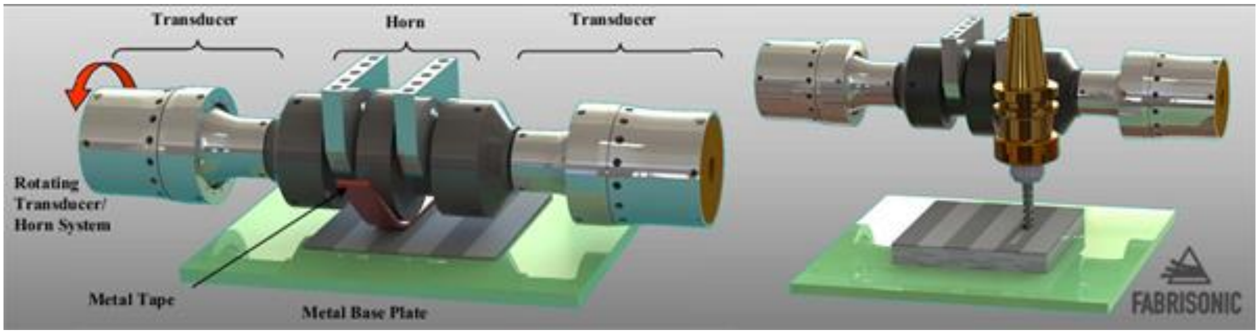

Figure 2.9.1: Ultrasonic Consolidation Process
www.rapidreadytech.com

Similar in principle to laminate layer manufacturing, USC uses thin metal plates or foil to build a solid metal part (White, 2003; Pal & Stucker, 2013). The process begins by laying down a plate of the desired metal onto the build surface and fixing it with a clamp or an epoxy. A CNC mill then cuts out the desired geometry of the slice. Another plate or layer of foil in then laid into the first layer. An ultrasonic welder then welds the shape of the next slice into the previous layer, and the unfused material is cut away with the milling machine. This process repeats until a certain thickness is accomplished, at which point a smaller end mill trims the part to the desired tolerance and surface finish. The whole process is repeated until the part is completed (Gibson et al, 2010, pg. 214-219; White, 2003; Obielodan et al, 2010).

In addition to building parts from scratch, this process can be used to add features to existing parts or to repair damaged areas (Gibert et al, 2013). USC also holds a lot of promise for the manufacture of multiple-material metal components and metal parts with imbedded electronics or sensors (Siggard, 2006). ***Figure 2.9.2*** shows a typical part created with this process. The materials typically used are titanium, steel, copper, nickel, aluminum, and various alloys and metal composites (Gebhardt, 2012, pg. 55). The major concern with using this process is the possibility of defects in the welds and cracks or voids between the layers (Gibson et al, 2010, pg. 222). The usual machine used to manufacture parts with this process is offered by Solidica of Michigan. This machine consists of a CNC milling machine with an integrated ultrasonic welding device, and a feeding system for metal strips to be used as raw material (Gebhardt, 2012, pg. 55).

Figure 2.9.2: Part Created with USC
www.lboro.ac.uk

2.10. Special Process - Contour Crafting

Figure 2.10.1: Use of CC to Build House
dailytrojan.com

This new and interesting process, while not defined as an AM process by the ASTM F2792-12a standard, shows promise to help automate building construction and repair. Contour crafting (CC) was developed at the University of Southern California by Dr. Behrokh Khoshevis for the purpose of rapidly constructing and repairing buildings (***Figure 2.10.1***) (Khoshevis, 2004). Dr. Khoshevis holds dozens of patents related to this process.

Figure 2.10.2: Contour Crafting In Operation
archive.cooperhewitt.org

In reality, the process is a combination of the principles of other AM processes, especially the material extrusion and sheet lamination processes. The setup for the process is a large gantry, crane, or robotic arm that is computer-controlled (Bosscher et al, 2007), to which a print head is attached that extrudes out the building material in layers (Zhang & Khoshevis, 2013). A series of computer-controlled tools finish each layer as it is printed. The material is either chemically activated cement or a binder-infused powder to create an adobe-like structure, but the process allows the application of multiple materials in a single building since it can use series of extrusion nozzles to lay out the material (Khoshevis, 2004).

The major advantages of this are speed, build quality, labor reduction, the ability to “print” a series of customized houses, and the possibility of embedding all of the home’s electrical, plumbing, and air conditioning needs as the home is being built. Even operations such as tiling and painting can be done during the build, allowing construction of a read-to-move-in house in a single process. As can be seen in ***Figure 2.10.2***, contour crafting allows for the rapid construction of very complex construction features, such as domes, vaults, and buttresses (Khoshevis, 2004). The major applications of this process are the construction of good emergency, low-income, and commercial housing quickly, and cheaply (Yeh & Khoshevis, 2009). Dr. Khoshevis’ current research project is to adapt the technology to be able to print structures and complexes on extraterrestrial surfaces, since this seems to be one of the only feasible means of doing so (Khoshevis et al, 2013).

2.11. Special Process – Cold Gas Dynamic Spraying

Sometimes called gas dynamic cold spray manufacturing, this process is similar in principle to the powder deposition process but with no heat or melting involved. It was developed in the USSR in the 1980’s to do cold repairs and coatings on solid parts and has some promise as an AM process (Sova et al, 2013; Pattinson et al, 2007; Alkhimov et al, 1994).

In this process, powdered materials are accelerated in a converging-diverging nozzle to speeds of up to 1000 m/s and sprayed onto the build surface, as shown in ***Figure 2.11.1***. The kinetic energy given to the particles by the expansion of the gas in the nozzle is converted to deformation energy when the particles come into contact with the surface, causing plastic deformation and adhesion of the material to the surface. No thermal cycling is involved in the deposition or the fusion, making it easier to control cracks, distortion, geometric tolerances, and the microstructure of the material (Pattinson et al, 2007; Sova et al, 2013). The spray nozzle is moved back and forth along the surface, evenly depositing the particles and building up the part. Metals, polymers, and ceramics can be deposited easily, as well as composite materials. The gas could be helium, nitrogen, or compressed air, depending upon the material and application (Sova et al, 2013; Choi et al, 2007).

Figure 2.11.1: CGDS Process
www2.cntrline.com

2.12. Special Process – Aerosol Jet Printing

Aerosol jet printing (also known as simply aerosol printing) is an interesting variation of the material jetting process that is used to print tiny electronic components, circuits, and even living cells (King & Ramahi, 2009; Paulsen et al, 2012; Gebhardt, 2012, pg. 56). The raw material is an ink that that could be metallic, polymeric, ceramic, insulator, or biomaterial, allowing an aerosol printing machine to produce conductors, semi-conductors, resistors, dielectrics, and a variety of other things (Hedges & Marin, 2012; Swiecinski et al, 2013). An atomizing chamber creates small particles of the material before sending them to the print head to be deposited on the printed surface, as shown in ***Figure 2.12.1***. This process is extremely accurate and gives fine detail, allowing the creating of extremely complex miniature components (Mahajan et al, 2013; Gebhardt, 2012, pg. 56). An interesting application of this process is the possible creating of flexible electronics and of imbedding electronics into 3-D parts created using other AM methods (Liu, R., et al, 2013). The process is commercialized by Optomec of Albuquerque, New Mexico.

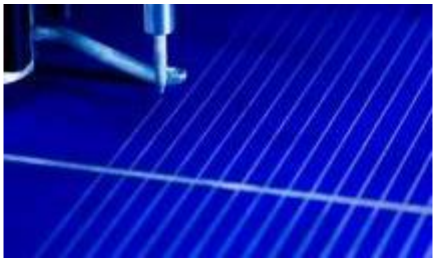

Figure 2.12.1: Aerosol Jet Printing
www.ikts.fraunhofer.de

2.13. Special Process – Bioplotting, Friction Surfacing, and Ice Prototyping

Bioplotting a special variation of the material jetting and material extrusion processes; its primary application is the medical industry. Typical bioplotting machines jet out the material and have the ability to utilize several fusion methods, including precipitation, phase transition, and chemical reactions (Gebhardt, 2012, pg. 57). The process can additively create structures using a wide variety of materials, including polyurethane, silicon, bone material, drug (such as PCL), soft tissue materials like collagen and fibrin, and living cells. This process is has been used to create bone structures, artificial organs, and artificial skin (Marga et al, 2012; Bergmann et al, 2010; Gebhardt, 2012, pg. 56-57; Mironov et al, 2007). Some of the specific techniques used to accomplish the printing are syringe deposition, inkjet printing, cell patterning, and soft-lithography (Guo & Leu, 2013).

Friction surfacing, sometimes called friction surface welding, is a solid-state friction coating process which can be used to both additively manufacture whole parts and to repair damaged regions in existing metal and ceramic parts (Dilip et al, 2013). This process works by creating a friction weld between a consumable material and a surface as it moves, securely depositing the material onto the surface (Gandra et al, 2013 & 2014). The most common materials to be deposited are steels and stainless steels. Since the consumable material is deposited onto the surface without melting the surface, it remains homogeneous, as does the surface (Hanke et al, 2013). The major advantage of this process is the possibility of quickly and cheaply welding dissimilar metals together with good mechanical properties (Dilip et al, 2013).

Dr. Pieter Sijpkes at McGill University in Canada created a machine to 3-D print solid objects out of water ice to be used to create ice sculptures and cheap prototypes. The process deposits the geometry by spraying thin films of liquid water into a super-cooled (-8°F) surface, building the part layer by layer (Liou, 2008, pg. 254-256). To prevent interruption of the water flow to the part, the jet that sprays the water onto the cold surface is kept at about 68°F (www.fabathome.org). The process is often known as freeze prototyping (Guo & Leu, 2013).

Chapter 3: Applications of Additive Manufacturing Technologies

3.1. Introduction

ASTM defines additive manufacturing (AM) as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM, 2012). A number of different applications for this technology exist, of which seven will be discussed in this paper. Rapid prototyping, rapid manufacturing, and rapid tooling are the major applications normally associated with AM. However, there are four others that should be considered important individual application of AM; these are secondary additive manufacturing, multiple-material manufacturing, functionally-graded material manufacturing, and hybrid layer manufacturing.

3.2. Rapid Prototyping

The original and still most used application of the AM technology is rapid prototyping**.** The process is defined as the "additive manufacturing of a design, often iterative, for form, fit, or functional testing or combination thereof" (ASTM, 2012). In practice, a prototype is defined as a "working [physical] model [that] is constructed to permit full evaluation of a product" (Black & Kohser, 2008, pg. 199). All of the major AM processes discussed in *Chapter 2*, with the possible exceptions of electron beam melting and contour crafting (due to cost), can be utilized for rapid prototyping. However, the most common ones used are the vat polymerization process (such as stereolithography), material jetting process (such as Polyjet), material extrusion process (such as FDM), sheet lamination process (such as LLM), and some of the powder bed processes (such as laser sintering) (Liou, 2008, pg. 243-293).

Product definition is the "process of translating customer needs into product design specifications" (Liou, 2008, pg. 5). In practice this definition is not so simple; there are many important aspects to product definition that need to be considered when creating a product. These are requirements definition, problem definition, conceptual design, design-for-assembly (DFA), design-for-manufacturability (DFM), and concept evaluation (Liou, 2008, pg. 4-7). All of these important product design steps should be modelled, in order to guide the design team, verify specifications, justify design decisions to management, and help customers to better understand the design (Liou, 2008, pg. 19). Ideally, the product definition phase is iterative and good prototypes are an important part of this (Van Eijk et al, 2012; Black & Kohser, 2008, pg. 199). A good computer-aided-design (CAD) model can serve some of the purposes of prototyping but not all, as a physical model is required for form and fit testing and proper evaluation of the concept (Black & Kohser, 2008, pg. 199).

Figure 3.2.1: Typical Models Made With Rapid Prototyping
lab.visual-logic.com, www.ast2.net, and www.ashokuk.co.uk

The construction of prototypes is certainly possible using traditional manufacturing methods, such as milling, casting, or injection molding. This was the standard until rapid prototyping was invented in 1986. Previously it was a very costly, complex, and expensive process, but one that was necessary for successful product development (Gibson et al, 2010, pg. 8). Enter rapid prototyping. The AM technology allows the manufacture of fine prototypes directly from CAD data, saving a massive amount of time and resources over old methods of modeling and prototyping (Novakova-Marcincinova et al, 2012). The layer-by-layer construction of the parts allows for the quick construction of incredibly complex prototypes as seen in ***Figure 3.2.1*** (Novakova-Marcincinova et al, 2012), and good medical models (Hieu et al, 2005).

3.3. Rapid Manufacturing

Alternatively known as direct digital manufacturing (DDM), rapid manufacturing is the utilization of additive processes to produce final-use parts and products, as opposed to the creation of models or prototypes. Although not defined by ASTM F2792-12a standard, it is nonetheless an important application of layered manufacturing technology. It would seem that rapid manufacturing is a natural extension and refinement of rapid prototyping, but in reality it is a different science all together (Munguia et al, 2008; Gibson et al, 2010, pg. 363). There are many important considerations in manufacturing that do not occur in prototyping, such as certification of equipment, materials, and personnel, quality control, logistics, and integration. The equipment should be regularly checked and calibrated, the raw materials should come from a known, reliable, and certified source, the personnel should be carefully trained, the process quality should be strictly controlled, and the logistics and system integration aspects need to be considered and planned. In order to accomplish all of this, industry standards must be fully and carefully followed (Gibson et al, 2010, pg. 372-374; Comb, 2010; Novakova-Marcincinova et al, 2012). It is far more important in rapid manufacturing for the parts to be as close as possible to perfect, than it is in rapid prototyping (Daneshmand et al, 2013; Pandey et al, 2007). ***Figure 3.3.1*** shows some typical products created by rapid manufacturing. All of the manufacturing processes discussed in Chapter 2 can be employed to do rapid manufacturing.

The reasons to use rapid manufacturing depend heavily on the application and the size of the project, but in general there are eight major gifts that are offered by all the AM process over traditional manufacturing methods for making end-user products. These are the elimination of tooling in the manufacturing process, unique geometry, complex geometry, lot size of one, fast turn-around, digital manufacturing, the digital record, and production on demand (Gibson et al, 2010, pg. 370-371; Petrovic et al, 2011; Santos et al, 2006). The elimination of hard tooling is one of the most important and revolutionary aspect of AM and the basis for many of the other advantages of the technology. Additive layer manufacturing offers the possibility of very unique and complex geometry, due to the inherent characteristics of the layered processes; this allows for more daring and revolutionary designs and helps improve the performance of product. Components are produced one-at-a-time without the need of special tooling, making it economical to produce just one of a particular product; this opens the door to mass customization (Tuck & Hague, 2006, Eyers & Dotchev, 2010, & Rochus et al, 2007).

Figure 3.3.1: Typical End-User Parts Made By Rapid Manufacturing
www.dpaonthenet.net, www.makepartsfast.com, and www.machinery.co.uk

Also due to the elimination of tooling and the click-and-go nature of AM machines, the manufacturing lead time for a project is drastically reduced, saving time and money for the manufacturer and increasing customer satisfaction. The fact that the manufacturing is directly from a CAD model reduces the chances of miscommunication between the designer and the manufacturer and allows the storage of a reusable dataset or digital record of the product. Finally, the ability to produce components on demand reduces or eliminates the need to hold inventory, dramatically reducing holding costs and storage fees for a manufacturing facility (Gibson et al, 2010, pg. 371-372; Hopp & Spearman, 2008, pg. 50).

3.4. Rapid Tooling

There are two definitions for the term “rapid tooling” defined by the ASTM F2792-12a standard. Classically, rapid tooling is the “production of tools or tooling quickly by subtractive manufacturing methods, such as CNC milling” (ASTM, 2012). With the recent advancements and improvements in AM technology, this tooling production can now be done using additive processes. This gives us a second definition: rapid tooling is the “use of additive manufacturing to make tools or tooling quickly, either directly, by making parts that serve as the actual tools or tooling components, such as mold inserts, or indirectly, by producing patterns that are, in turn, used in a secondary process to produce the actual tools” (ASTM, 2012).

Figure 3.4.1: Plastic Injection Molding Dies
www.9to5seating.com

Rapid tooling is effectively a special application of rapid manufacturing and has the same benefits, namely the elimination of hard tooling, the unique and complex geometry possible with an additive process, the ability of the process to economically produce just one tool, the small lead time to production, the digital recording of the tooling production process, and the ability to produce tools on demand (Gibson et al, 2010, pg. 370-371). In addition, the additive manufacture and additive repair of tooling is less energy-intensive and more environmentally sustainable than a CNC process would be (Morrow et al, 2007). The final result is the creation of tooling to be used in a traditional manufacturing process, as opposed to end-user products. ***Figure 3.4.1*** shows the tooling for a plastic injection molding process; as can be seen, the geometry is very complex.

Figure 3.4.2: Hybrid Modular Tooling
Kerbrat et al, 2010

Tooling is defined as a “mold, die, or other device used in various manufacturing and fabrication processes such as plastic injection molding, thermoforming, blow molding, vacuum casting, die casting, sheet metal stamping, hydroforming, forging, composite lay-up tools, machining, and assembly fixtures” (ASTM, 2012; Violante et al, 2007). This tooling could be created using a traditional CNC process or using an AM process. If creating it with an additive process, there are two possibilities; the first is to create it directly, while the second is to create a mold or pattern for the tool that will be made later (Corcione et al, 2006). If using the AM process to create the tooling, it can more easily be made with inserts and adjustable features (modular hybrid tooling – ***Figure 3.4.2***), expanding its usefulness (Kerbrat et al, 2010). There are also a lot of medical and dental applications for the rapid tooling technology (Salmi et al, 2012 & 2013).

Figure 3.4.3: Plastics Injection Molding Tool
www.ilt.fraunhofer.de

The most common and important direct rapid tooling application is various dies for pressure forming processes, such as plastic injection molding and metal die casting (Pessard et al, 2008; Dormal, 2003; Pereira et al, 2012). In addition to the standard advantages offered by AM, the ability to create internal cooling channels into the tooling is a huge plus (notice the cooling channels built into the die in ***Figure 3.4.3***). Tools that contain the internal cooling channels have better cooling performance, resulting in a reduction of part cycle time and improvement of final part quality due to reduced thermal distortion (Rannar et al, 2007; Velnom & di Giuseppe, 2003). This tooling is usually made out of metal using one of the powder bed fusion processes discusses in *Section 2.6* (Abe et al, 2001; Akula & Karunakaran, 2006). Some feature creating, post-processing and hard facing can be done with a powder deposition process like LENS (Dutta et al, 2011).

In addition to being able to directly manufacturing tooling additively, it is also possible to print forms or molds to be used later to create the tooling. There are a number of different ways to do this with stereolithography (Corcione et al, 2006) and with a binder jetting process to create sand and ceramic molds and shells (Bassoli, 2007; Gebhardt, 2012, pg. 47-51; Black & Kohser, 2008, pg. 263 & 276-277). Other processes can be used as well, but are not as common (Wang, 2010, pg. 57). Another common application for rapid tooling is the creation of patterns for casting, where high accuracy and good surface finish are required but high strength is not a priority. Patterns for investment casting can be made from plastic, wax, or nylon using any of the additive processes that can produce parts made from these materials, particularly stereolithography, FDM, and laser sintering (Bassoli et al, 2007; Sun et al, 1989). This application will be discussed in more depth in *Section 3.5 Secondary Additive Manufacturing*.

3.5. Special Application - Secondary Additive Manufacturing

While technically a branch of rapid tooling, secondary AM is distinctive because the process does not directly create a prototype, end-user part, or tooling. The result is an object that will then be used to create a prototype, part, or tool using a secondary casting process. This is distinct from the direct printing of forms or molds, as discussed in *Section 3.4 Rapid Tool*ing, because the directly printed forms can be considered to be tooling. Secondary AM is usually done to create masters for various casting processes, particularly investment casting and lost-foam casting (Sun et al, 1989; Gibson et al, 2010, pg. 412-416). It can also competently create hard master parts for sand casting, as discussed in *Section 3.4 Rapid Tooling*. Secondary AM is sometimes called rapid casting and indirect rapid tooling (Bassoli et al, 2007; Chhabra & Singh, 2011; Tromans, 2003).

Investment casting masters are hard parts with relatively low melting points made with good accuracy and good surface finish; good strength is a secondary consideration. The masters could be created out of plastic, wax, nylon, aluminum, or any other stable material with a relatively low melting point that is easy to work with. The master is then dipped into slurry of finely ground silica or other material in order to completely coat the part and the layer is allowed to dry. This is repeated several times until the layer of slurry is stable and hard. The whole thing is then placed into a furnace to melt out and burn away the master part, leaving an excellent mold to be used to cast a more difficult material (Black & Kohser, 2008, pg. 304-306). AM techniques are well suited to creating the master parts, particularly stereolithography, material extrusion, sheet lamination, and powder bed fusion processes (Wang, 2010, pg 59-66). ***Figure 3.5.1*** shows an additively manufactured master part for the investment casting of jewelry.

Figure 3.5.1: Master for Investment Casting
envisiontec.com

In lost foam casting, a foam or light plastic (such as polystyrene) master part (similar to the one in ***Figure 3.5.2***) is buried fully in a sand bed, with an opening from the master to the surface. When the molten material is poured into the cavity, the foam is melted, burned, and replaced by the molten metal. When manufacturing the masters in small quantities, they can be made by hand or cut with a machine (Black and Kohser, 2008, pg. 308-310). When many are needed or when they need to be very fine and consistent they can be molded or additively manufactured. While molding is faster, once the tooling is created, the additive process gives more flexibility, allows small design modifications and saves the cost and lead time of the tooling. The castings are infinitely customizable due to the properties of AM (Bassoli et al, 2007; Chhabra & Singh, 2011).

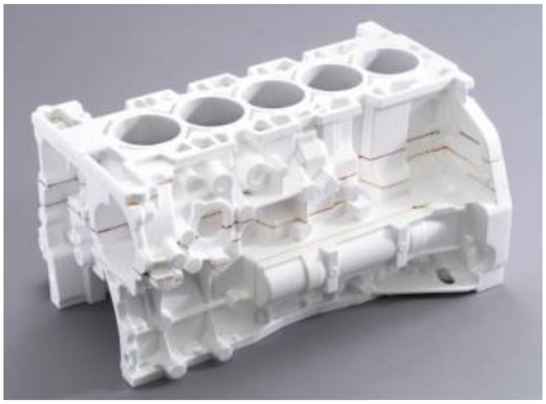

Figure 3.5.2: Master For Lost Foam Casting
www.nitromag.fr

3.6. Special Application – Multiple-Material Manufacturing

Due to the layer-based characteristics of AM, it is ideally suited for the construction of multiple-material parts. Multiple-material components are those made from two or more materials, but the various materials are distinct from each other; they are arranged into a composite material, usually in layers (Choi et al, 2011; Gibson et al, 2010, pg. 423). Multiple-material components offer many benefits over single-material ones. The common reasons to utilize several materials in a part are to enhance the functionality, the mechanical properties, the freedom of the design, and the stability of the material. However, there are many application-specific reasons to desire a multiple-material design; things like enhanced local thermal properties and hardness, high temperature resistance, better properties for turbine components and thermal coatings, improved optical and magnetic properties, optimized chemical properties for batteries, and superior acoustic properties for musical instruments are all good reasons to design multiple-material

Figure 3.6.1: Multiple-Material Part
www.deskeng.com

components when possible. Also possible is the creation of electric circuits and the embedding of objects, such as sensors and electronics, into parts as they are manufactured (Vaezi et al, 2013; Gibson et al, 2010, pg. 424-427 & 431-432; Oxman, 2010). Multiple-material manufacturing is uniquely suited to create imitations of natural structure, such as insect legs, which have a large range of applications for use in biomedical and robotics applications (Cutkosky & Kim, 2009). ***Figure 3.6.1*** shows a sample of a multiple-material prosthetic socket.

Multiple-material AM can be done with most of the processes discussed in *Chapter 2*. However, the normally employed processes are stereolithography, FDM, powder bed fusion, powder deposition, sheet lamination, material jetting, binder jetting (Vaezi et al, 2013; Lappo et al, 2003; Kim et al, 2010; Choi et al, 2010; Oxman Report, 2011) and ultrasonic consolidation (Ram et al, 2007; Obielodan et al, 2010). There are processes that use SLS, but deposit the powder with a nozzle instead of a roller, in order to selectively place the powder in each layer (Lappo et al, 2003).

3.7. Special Application – Functionally-Graded Material Manufacturing

Functionally-graded components are made from a single material but, due to the production process or material treatments, have functionally variable properties; in other words, composition and structure varies throughout the material by design, affecting the mechanical properties (Oxman, 2011 & 2012; Muller et al, 2013; Oxman Report, 2011).

Functionally-graded materials are engineered to have specific functionalities and applications. There are a number of ways to create them, including powder processing, layer processing, and melt processing. The variations in the material are designed for a particular application though the careful creation of material regions with unique chemical and structural properties. Functionally-graded materials are very important to materials science and mechanics, as it allows the integration between material considerations and structural concerns; these are effectively “designer” materials in terms of local physical properties (Oxman, 2011; Gibson et al, 2010, pg. 295-296; Oxman et al, 2011). These customized materials have a lot of applications in aerospace, biomedical, dental, structural, optical, and electronic applications (Wang & Shaw, 2006; Traini et al, 2008). ***Figure 3.7.1*** shows the structure of a functionally-graded material; the transition between regions can be clearly seen.

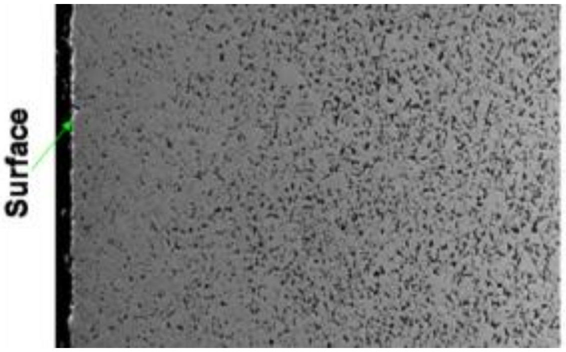

Figure 3.7.1: Model Of FGM Structure
powder.metallurgy.utah.edu

AM can be used to create functionally-graded material parts through four major choices of processes. The first is to use a powder deposition process such as LENS to create the material; this is a good choice for metallic or ceramic materials, as the process is easy to control. Next, a jetting process such as 3DP or Polyjet could be used; this is a good choice for polymeric materials, inks, and ceramics (depending upon the application). The third option is to use a laminate layer process and control the binder application to control the functional properties. Finally, a powder bed fusion process such as laser sintering could be used to create functionally-graded parts (Wang & Shaw, 2006; Gibson et al, 2010, pg. 295-296; Muller et al, 2013 & 2014).

3.8. Special Application - Hybrid Layer Manufacturing

Traditional subtractive metal manufacturing processes such as CNC milling produce excellent geometric tolerances and surface finish on parts, but are slow, expensive, and limited by the complexity of the project. AM technologies such as powder deposition, on the other hand, are fast, less expensive, and can create nearly any geometry but lack the fine finish and dimensional tolerances. Why not combine the best of both into a single process? Welcome to hybrid layer manufacturing (Karunakaran et al, 2004 & 2009).

The premise of hybrid layer manufacturing is the marriage of traditional CNC milling with AM. This helps to mitigate some of the disadvantages of both processes, dramatically speeding up the process while expanding its capabilities (Kerbrat et al, 2011; Karunakaran et al, 2010). The major problem using the hybrid process is the issues that come up when designing the products to be manufactured, due to the fact that there is no standard design-for-manufacturability method to combine the two processes (Kerbrat et al, 2011). As seen in ***Figure 3.8.1***, the part features are created quickly with a powder deposition process (LENS) and are then cleaned up, finished, and brought to tolerance with the CNC milling process. The additive process is able to quickly add features that the mill would not be able to create easily or economically (Karunakaran et al, 2010).

Figure 3.8.1: Hybrid Layer Manufacturing
www.economist.com

A major application for hybrid layer manufacturing is the speedy creation of excellent tooling for injection molding and die casting processes (Akula & Karunakaran, 2006). By combining the processes, modular tooling (tooling with adjustable features) is easier to design and create (Kerbrat et al, 2010 & 2011). While the combined process can be designed to be stand-alone, the combination is so simple that it can easily be integrated into an existing CNC milling machine that had the space and the proper controlled environment for the powder deposition process (Karunakaran et al, 2009). There is an alternative process that uses a plasma torch as the power source (Xiong et al, 2007), but the LENS method seems to be preferred. A two-step process is also possible using additive processes besides powder deposition (such as selective laser melting), but this requires the physical movement of the work piece between machines (Kerbrat et al, 2011).

Chapter 4: Relevant Economic Sectors

4.1. Introduction

This far in this paper, the basics of additive manufacturing (AM) have been discussed; the basic theory, the history, the essential processes (with selected special cases), and the important applications (again, with a few special cases). This section will discuss the relevant economic sectors that AM could logically offer a benefit to. While this list is extensive, it is by no means exhaustive; these are simply the most common and widely-discussed uses for the technology that are developed or under development.

4.2. Aerospace Technology

The aerospace industry is one of the most important users of AM and receives three major benefits from utilizing the technology: the ability to produce superior and optimized parts (both direct manufacturing and tooling), the ability to create excellent models and prototypes, and the ability to repair large and expensive parts.

Figure 4.2.1: Optimized Aerospace Part
blog.sculpteo.com

Figure 4.2.2: Complex Rocket Component Made By AM
www.industrial-lasers.com

Manufacturing aerospace parts using traditional methods is a very complex and expensive business, as these operations are limited in design complexity, are slow, and are very wasteful of pricey raw materials such as titanium and nickel alloys. While the physical properties are not (yet) quite as good as parts made with traditional processes (Daneshmand et al, 2013; Hiemenz, 2013), AM allows the designs to be optimized without the normal manufacturing limitations, reduces the cost of manufacturing, reduces the weight of parts and products, and minimizes energy and material waste (Dehoff et al 2013; Petrovic et al, 2011; Wong & Hernandez 2012; Rockel et al, 2013). Almost any geometry can be easily created using AM, including pockets and lattice structures, multiple-material and functionally-graded features, and conformal cooling channels; this has strong impacts on the weight, strength, toughness, and heat and vibration properties of components (Raja et al, 2006; Guo & Leu, 2013; Gibson et al, 2010, pg. 439; Bernstein et al, 2013). ***Figure 4.2.1*** shows a redesigned part for an aerospace application compared to the part it replaced. The new part shows significant material and weight reduction and increased design complexity. A very complex rocket engine component is shown in ***Figure 4.2.2*** which was made by NASA using additive AM.

The primary purpose of rapid prototyping is to shorten product development, providing a model for visual inspection, fit testing, and wind-tunnel analysis (Vashishtha et al, 2011). Wind-tunnel tests are a standard part of aircraft development and good scale models are needed for the tests. Rapid prototyping allows complex and customized models to be made quickly and cheaply (Chuk & Thomson, 1998; Daneshmand et al, 2006). A model of an experimental aircraft created by rapid prototyping is shown in ***Figure 4.2.3***. The typical process used to repair large components is LENS or another laser powder deposition process (Xue & Islam; Hedges & Calder). Typical engine components that need repair are blades, compressors, turbine and combustor casings, and housing parts; however, more complex parts such as vanes, stators, rotors, airfoils, and ducts have been successfully repaired. Repairing these components serves to reduce the cost, extends the lifetime of the parts, and prevents downtime on aircraft (Guo & Leu, 2013; Mudge & Wald, 2007). See ***Figure 4.2.4*** for an example of a LENS building of a turbine blade.

Figure 4.2.3: 3-D Printed Model Aircraft
www.shapeways.com

Figure 4.2.4: LENS Building of Blade
www.lia.org

4.3. Automotive Technology

Automotive technology is an obvious application of the technology, since there is a great need for concept models and prototypes, as well as high-quality, specialized, low-cost, and low-weight components, similar to the needs of the aerospace industry. Additive technologies offer the ability to create prototypes during the design and development and the capability to directly fabricate specialized components and tooling needed to make high-quality and plentiful cast and injection molded components (Gebhardt, 2012, pg. 73-76; Regelmann, 2003). The technology offers much freedom of design, freedom from some traditional manufacturing limitations, weight- and cost-reduction of parts, reduced design and product development cycle time, and the minimization of energy and material waste (Wong & Hernandez 2012; Guo & Leu, 2013).

Figure 4.3.1: Prototype Car with Printed Body
www.industrial-lasers.com

In terms of manufacturing, the major areas where the automotive industry could benefit most from utilizing this technology are structural application, engine components, and plastic components. While it is certainly possible to print large parts, such as the body (***Figure 4.3.1***), but it is not practical usually (Regelmann, 2003; Urbee, 2014; Petrovic et al, 2011; Wong & Hernandez 2012).

For structural and engine components, AM offers the ability to easily make pockets, holes, and web structure, and multiple-material and functionally-graded features (Guo & Leu, 2013), heavily impacting the strength, toughness, weight, and heat and vibration properties of components used (Rockel et al, 2013; Regelmann, 2003). Rapid tooling and secondary AM have many important uses in automotive technology, particularly in the manufacture of tooling for injection molding of small plastic components (***Figure 4.3.2***) and casting masters (***Figure 4.3.3***) (Pessard et al, 2008; Gibson et al, 2010, pg. 412-416).

Figure 4.3.2: IJM Automotive Component
www.exceedmold.com

Figure 4.3.3: Master Engine Casting
www.forbes.com

4.4. Biotechnology

Figure 4.4.1: Organ Structures Produced by AM
www.designboom.com

There are quite a few possible ways that AM technologies can be used for biotechnology applications, but there are two very important ones: the manufacturing of bio-compatible materials, or scaffolds, and biofabrication. There are three types of bio-compatible materials, namely those that have properties making them fit for use inside a human body (such as implants), those fit for uses outside the body (such as hearing aids), and bio-degradable materials (such as structures for artificial organs – ***Figure 4.4.1***) (Petrovic et al, 2011). Biofabrication is the creation of components or forms where the basic material is living cells. This is used to create a range of products, such as biological substances, medical devices, and replacement body parts (Guo & Leu, 2013; Liu, F., et al, 2013).

Biocompatible materials formed into 3-D scaffolds are vital to tissue engineering, as they provide the base to which living cells attach and grow to form new tissue and control the form and growth of new tissue (Lantada & Morgado, 2012; Nakamura et al, 2011). Traditionally, these scaffolds were formed using a casting, molding, or foam replication process; however, these were difficult to handle, the internal structure was hard to control, and they had poor reproducibility (Guo & Leu, 2013). AM can be used for both direct and secondary fabrication, allowing these essential scaffolds to be created easily, quickly, cheaply, and with customized structure (such as channels and lattices) (Nakamura et al, 2011; Vlasea et al, 2013; Castilho et al, 2011). Direct fabrication can be done with any of the basic additive processes, but the most practical ones (Guo & Leu, 2013) are laser sintering (Campoli et al, 2013), stereolithography (Melchels et al, 2010; Bian et al, 2012), 3DP (Bose et al, 2013), and FDM (Zein et al, 2002); bioplotting, a combination of the material jetting and material extrusion processes, and aerosol printing are commonly used as well (Gebhardt, 2012, pg. 56-57). Secondary AM can be employed when a form or mold is desired to create a part from a biomaterial; this is especially useful when creating artificial bones (Yoon et al, 2012; Warnke et al, 2009), shown in ***Figure 4.4.2***. Hybrid processes combine the best of AM and traditional processes (such as micro syringe deposition) in order to generate custom properties in the material (Vlasea et al, 2013).

Figure 4.4.3: Biofabrication of Artificial Organ
www.singularityweblog.com

Biofabrication is the construction of objects out of living cells. There is a massive range of possible applications for biofabrication, including tissue engineering, disease pathogenesis, drug delivery, chips and sensors, and organ printing (Guo & Leu, 2013; Marga et al, 2012). When partnered with a scaffold created out of a biocompatible material, it is possible to create whole artificial organs, as seen in ***Figure 4.4.3*** (Melchels et al, 2012; Andersen et al, 2013; Nakamura et al, 2011; Oliveira et al, 2012). In addition to the standard bioplotting, aerosol printing, and material jetting processes, there are several hybrid biofabrication processes that utilize aspects of AM. Some of these AM-based processes are syringe-based deposition (Chang et al, 2010), inkjet printing (Cui & Boland, 2009; Boland et al, 2006), cell patterning (Roth et al, 2004), and soft-lithography (Chang et al, 2010).

Figure 4.4.3: New Bone Produced with AM
www.forbes.com

One of the major benefits offered to the biotechnology world by AM is its ability to use a huge variety of raw materials, including polymers (Petrovic et al, 2011), ceramics (Shanjani et al, 2010; Goffard et al, 2013), metals (Murr et al, 2009; Campoli et al, 2013), hydrogel (Billiet et al, 2012), living cells (Melchels et al, 2012; Mironov et al, 2007), and bacteria (Connell et al, 2013), which are all essential to biotechnology research and applications. Of these materials, polymers are the most common and important; they can be used to create both internal and external medical devices and biodegradable objects, such as structures for artificial organs (Petrovic et al, 2011).

4.5. Medical and Dental Technology

One of the earliest applications of rapid prototyping was the creation of medical models; however the technology has developed so far since those early days that it is used for many medical- and dental- related purposes. The most important reason to use AM technology to produce medical and dental devices is its ability to create custom products quickly and at lower cost compared to traditional methods. There are four major areas where AM benefits the medical and dental industries, namely surgical and diagnostic aids and models, prosthetic development, manufacturing of medical devices, and tissue engineering (Gibson et al, 2010, pg. 386-387; Petrovic et al, 2011). Tissue engineering is only relevant to medical applications and was addressed in *Section 4.5 – Biotechnology*; the other three will be discussed here in the context of both medical and dental fields.


Figure 4.5.1: Model of Foot
www.electronicproducts.com


Figure 4.5.2: Dental Model
envisiontec.com

Diagnostic models are very important to surgeons and patients in the same way that prototypes are important to engineers and customers (Lantada & Morgado, 2012; Gibson et al, 2010, pg. 387). Doctors and dentists need reliable models in order to communicate with each other, to plan procedures, and to assist patients in understanding what is to be done. Having good models can also reduce to the time required for a surgery, due to better planning and understanding by the patient and surgical team (Truscott et al, 2007; Giannatsis & Dedoussis, 2009; Traini et al, 2008; Hieu et al, 2005). Traditionally, these models are made by hand, one at a time, out of plaster or other ceramic; this is a very time consuming process and does not offer the accuracy, detail, customizability, or miniaturization abilities that AM processes give (Salmi et al, 2013; Ibrahim et al, 2009; El-Katatny et al, 2010; Werner et al, 2010; Kim et al, 2014; Gebhardt, 2012, pg. 91; Wicker et al, 2004; Cohen et al, 2010; Nizam et al, 2006). ***Figure 4.5.1*** shows a model of a foot, with the bones and structure clearly visible and ***Figure 4.5.2*** shows a dental model made directly by rapid prototyping from a scan of the patient's mouth for the fitting of a crown.

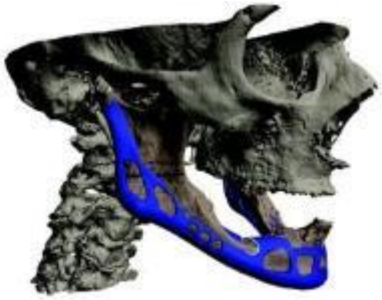
Figure 4.5.3: Model of Jaw Implant
www.designnews.com

In addition to the diagnostic aid models, AM is also very useful in the design and development of prostheses, implants, crowns, and medical devices. The capability of additive processes to create complex and infinitely-customizable objects is what drives it use in this area (Gibson et al, 2010, pg. 389; Truscott et al, 2007). Each implant or prostheses is a custom product, made directly for one particular patient, such as jaw implant in ***Figure 4.5.3***, and facial implants (He et al, 2006; Lantada & Morgado, 2012; Hao et al, 2009; Herlin et al, 2011; Klammert et al, 2010). Creating good and cheap prototypes can significantly reduce the time required to design one of these devices. The automated nature of AM also reduces the possibility of human error and miscommunication when building such products (Traini et al, 2008). All of the needed adjustments are done with the prototype, so that the implant or device only has to be set in once; this speeds recovery time and long-term operation success for the patient (Gibson et al, 2010, pg. 389). Freedom of design, easily obtainable from AM, allows the design of implants with lattice structures and variable properties, saving weight and material and making the devices more comfortable and more customized. Exterior medical devices can be created using the same principles, such as customized casts (such as that in ***Figure 4.5.4***) or prosthetic limbs (as seen in ***Figure 4.5.5***) (Traini et al, 2008; Hieu et al, 2005).

Figure 4.5.4: Custom Arm Cast Made by AM
www.medgadget.com

Figure 4.5.6: Skull Implant
www.rtejournal.de

The third major use of AM technology in medical and dental work is the actual manufacture of devices such as implants and prostheses (See ***Figures 4.5.4 & 4.5.5***), which is the logical next step after creating finalizing the design with prototypes (Murr et al, 2009). Implants and devices are typically made from metal (titanium or stainless steel) and use SLS, SLM, or 3DP (using metal powder) to do the consolidation (Leu et al, 2008, pg. 150-152; Gao et al, 2009; Gebhardt et al, 2010; Hao et al, 2009). More common than direct manufacturing is the creation of tooling, forms, and patterns to be used in molding or lost wax casting of the final products (Gebhardt, 2012, pg. 91-93; Salmi et al, 2012). ***Figures 4.5.6 and 4.5.7*** show a skull implant and a titanium bridge that were manufactured using additive processes.

Figure 4.5.7: Titanium Bridge
www.eos.info

Figure 4.5.5: Prosthetic Leg Made by AM
www.preceden.com

4.6. Chemistry and Materials Technology

A paper published in May 2012 discusses the possibility of using AM processes to create chemical compounds and medicines, including “designer” compounds that do not yet exist (Symes et al, 2012). The process uses a cheap off-the-shelf 3-D printer which prints chemical ink (reactants), which react with the base material and create a custom chemical compound. There are four major possible future uses of this process: printing custom and on-demand pharmaceuticals, medical diagnostics, education, and chemistry research (Khaled et al, 2014; Symes et al, 2012; Johnson, 2012). Many chemical compounds are created by bringing the ingredients together and causing a selective chemical reaction; instead of creating the compounds by hand, a basic 3-D printer could be easily retrofitted to do it. ***Figure 4.6.1*** shows a view of a chemical printing machine at the University of Glasgow in the UK.

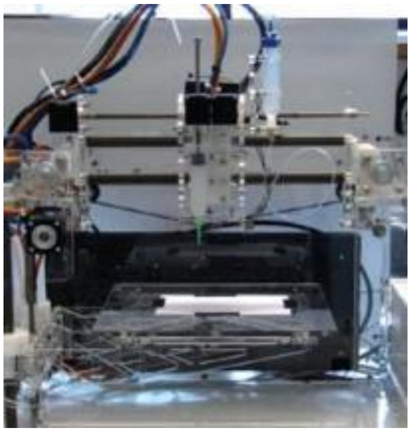
Figure 4.6.1: Chemical Printer
Symes et al, 2012

AM can utilize a huge range of raw materials, including resins, liquefied plastic, laminate material, powdered plastic and ceramics, and metals, such as stainless steel, titanium, and aluminum (Guo & Leu, 2013). These materials are formed with a large range of additive processes, from stereolithography to electron beam melting. From the perspective of materials science, the processes of deposition and fusion, the rapid thermal cycling, and solidification environment create some very complex conditions that severely affect the properties of the material, for bad or for good. For bad, it can cause problems with material homogeneity, surface finish, and dimensional accuracy (Petrovic et al, 2011; Berman, 2012; Pyka et al, 2012). However, if expected and properly modeled and controlled, these complex conditions have two very important benefits; functionally-graded materials (solid materials with variable properties throughout the geometry) and very complex lattice structures can be easily created by taking advantage of these special properties (Lu & Reynolds, 2008; Oxman, 2011 & 2012; Muller et al, 2013; Gibson et al, 2010, pg. 295-299; Rosen, 2007). ***Figure 4.6.2*** shows some samples of the possible material structures that can be made using AM.


Figure 4.6.2: Complex Material Design by AM
www.netfabb.com, www.mmsonline.com, www.sme.org

4.7. Nanotechnology

Nanotechnology is the application of science and engineering principles at the nanoscale level. Due to the ability of AM to produce very fine details, complex geometry and customized materials, a marriage between additive processes and nanotechnology could reduce the difficulties and limitations of nanotechnology and open the door to entire new applications (Ivanova et al, 2013).

Figure 4.7.1: Nanoscale Gears Made with AM
www.designboom.com

While in theory, nanotechnology is simply the scaling down of existing technology to a smaller size (such as the tiny parts in ***Figure 4.7.1***); in practice, this is far from true. One of the major issues with nanotechnology is that such shrinkage (from macro to nano) can cause the basic properties of the material to change (Ivanova et al, 2013). In particular, the optical, thermal (Jain et al, 2008), and electrochemical (Ivanova & Zamborini, 2010) properties are affected; these are heavily dependent on the size and geometry of the nano object (Burda et al., 2005). However, these unique or variable properties are not always a disadvantage; in fact, they can be quite useful for creating sensors (Liu & Tang, 2010), for studying plasmonics (Love et al, 2008), for measuring chemical reactions (Kolmakov & Moskovits, 2004), for making tiny electronics (***Figure 4.7.2***) (Sgobba & Guldi, 2009), and for building tiny medical devices (Cohen et al, 2010; Richter & Lipson, 2011; Ivanova et al, 2013; Sonvico et al, 2005).

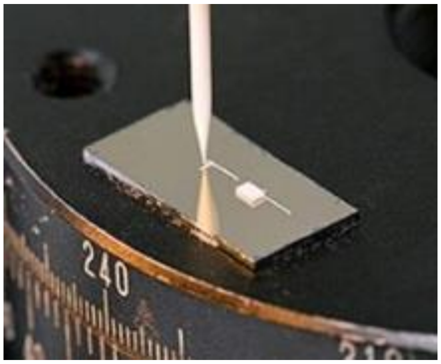

Figure 4.7.2: Nano Battery Made with AM
www.extremetech.com

Some of the many materials commonly used in nanotechnology are carbon nanotubes, graphene, metals, nanowires, and ceramics, all of which can easily be handled directly with or added to media used in AM. Thus, the partnership of nano materials and AM brings the possibility of creating entirely new materials and composites that have unique properties; this helps both AM and nanotechnology to further develop. Bringing the two together opens up new application areas and process capabilities for AM, while being able to use the additive processes to remove many of the headaches from manufacturing nanoscale objects (Ivanova et al, 2013).

4.8. Customized Consumer Goods

The manufacturing of consumer goods is sometimes difficult, as they not only have to fulfil a particular function but also have to be appealing and desirable for the customer. Consumer goods are items such as cell phone cases, sunglasses, dishes, lamps, and a huge variety of other things that will be used and handled by humans on a daily bases. Traditionally, these items were mass produced; however, the current demand for consumer goods is trending toward individualized products and away from standardization, necessitating the implementation of mass customization in order to remain competitive and offer the most desirable products to customers (Gebhardt, 2012, pg. 78; Liu et al, 2006; Merle et al, 2010). Mass customization is the ability of a producer to fulfil the various needs and desires of each customer without significant sacrificing of delivery, cost, or quality of the final products. The combination of the principles of craft manufacturing with the cost, speed, and quality of mass production gave birth to the concept of mass customization (Trentin et al, 2012; Dellaert & Stremersch, 2005; Lu & Storch, 2011, pg. 4).

AM is ideal for the production of customized consumer goods, as it offers almost infinite customization, freedom from traditional design constraints, and the elimination of hard tooling in the production process (Eyers & Dotchev, 2010; Rommel & Fischer, 2013; Petrovic et al, 2011). The possibility of nearly limitless customizability in designs is useful for both prototypes and for actual production parts. For products that will have the same features and geometry and will be customized in the materials and a prototype can be created quickly using material jetting or stereolithography to test form and fit before creating tooling for it, such as that seen in ***Figure 4.8.1***. If each part is unique or has custom geometry, direct manufacturing is a good choice. For items like lamps and vases, a number of items can be created in batches at once using stereolithography, material jetting, or a powder sintering process, all of which can have unique and customized features (Gebhardt, 2012, pg. 78-81; Reeves et al, 2011, pg. 276-279). ***Figure 4.8.2*** shows a sampling of customized consumer goods that could be created using AM, allowing each item to be unique.

Figure 4.8.1: Prototype and Product
proto3000.com

Figure 4.8.2: Cell Phone Cases, Vases, and a Custom Coffee Cup Created by Additive Manufacturing
cubify.com, printers.iyogi.com, www.shapeways.com

4.9. Open-Source Scientific Equipment

The beginning of most research projects is the identification and acquisition of required lab equipment. This could consist of purchasing the equipment, modifying existing holdings, or building new hardware from scratch. Most of the equipment will use some sort of software to run and complete experiments, which requires the use of computers. Open-source software can be used, as it is readily customizable and usually free of charge. In the past, it was usually easier to modify open-source software to run specialized experiments on general purpose equipment than it was to design and build customized hardware (Pearce, 2012).

Figure 4.9.1: 3-D Printed Medical Tools
Kondor et al, 2013

When open-source software is used in parallel with AM technology, it is a simple matter to not only create custom and specialized lab equipment, but also specialized tools using open-source production principles (Pearce, 2013; Wulfsberg et al, 2010; Crane et al, 2011; Johnson, 2012). Many research groups like to share their equipment designs, many of which can easily be created using AM, in order to benefit the process of science, in order to spread out the cost of said equipment, and to speed the refinement of the tools without having to deal with patents and delays when designing and fabricating custom scientific equipment (Pearce, 2013).

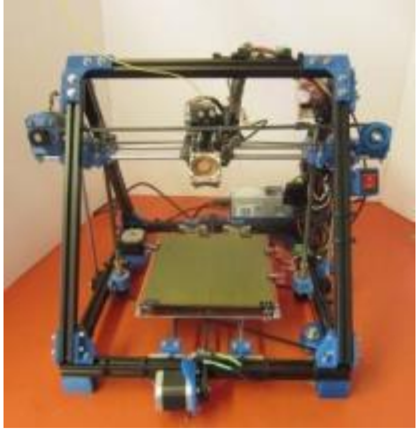

Figure 4.9.2: GP Open Source 3-D Printer
www.3ders.org

Equipment and tools could be anything from a simple pipette (Pearce, 2013) to custom optics (Zhang et al, 2013) to on-demand medical tools (Kondor et al, 2013) shown in ***Figure 4.9.1***, to a specialized printer that prints custom chemical compounds (see ***Figure 4.6.1*** in *Section 4.6 – Chemistry and Materials Technology*), to general-purpose open-source 3-D printers (***Figure 4.9.2***) that will give extra capabilities and flexibilities to a lab (Johnson, 2012; Wittbrodt et al, 2013; Pearce, 2012).

4.10. Heat Exchangers and Tool Cooling

As discussed in *Section 4.6 – Chemistry and Materials Technology*, the physical properties of materials that undergo AM processes are affected by the deposition and fusion, the thermal cycling, and the solidification method. This creates complex material conditions and very unique mechanical, thermal, and electrical properties which, when properly controlled, can be optimized for particular applications (Oxman, 2011 & 2012; Muller et al, 2013; Gibson et al, 2010, pg. 295-299; Rosen, 2007). This, along with the capability of AM processes to make extremely complex geometry, has a lot of benefits to offer in the design and fabrication of heat exchangers and radiators (Neugebauer et al, 2011) and other heat transfer devices, such as cooling devices in production tooling (Gibbons & Hansell, 2005).

Figure 4.10.1: Simple HEx Made by AM
Neugebauer et al, 2011

In any liquid heat transfer device, effective heat transfer requires as much contact as possible between the fluid and the device. An efficient and reliable device with a high surface-area-to-volume ratio is important for the most effective heat transfer. Traditional methods for making heat exchangers, radiators, and other heat transfer devices are often expensive and complex, requiring a huge number of individual parts. The most common methods of assembly are soldering and diffusion bonding, which are not reliable enough to ensure leak prevention, which can contaminate the fluids and cause system failure (Bergman et al, 2011, pg. 706-708; Ashman & Kandlikar, 2006; Neugebauer et al, 2011).

A better approach to the design and manufacture of heat exchangers is in a single piece using AM. The incredible detail and unique geometry that is possible with a process such as selective laser melting (Wong et al, 2007), as well as the customizability of the material and the speed of production, help to make excellent components without most of the traditional design headaches. The designs can be very intricate and closer to theoretical "perfect" heat exchangers than current designs. They can also be made more compact in order to maximize the effectiveness while making the most of the design space. There is a larger choice of possible materials with an additive process, including the possibility of using several materials in a single device. Best of all they are modular, without seams, and are much less likely to leak and to fail prematurely (Neugebauer et al, 2011; Wong et al, 2007 & 2009; Bergman et al, 2011, pg. 739).

Figure 4.10.2: Details of AM-Created HEx
m.technologyreview.com

In addition to being able to create superior versions of traditional designs, the technology can also create complex and tiny cooling channels within the exchanger in order to get the absolute maximum benefit from the space used for the exchanger (Petrovic et al, 2011; Neugebauer et al, 2011; Ashman & Kandlikar, 2006). ***Figure 4.10.1*** shows a simple modular heat exchanger creating using AM, while ***Figure 4.10.2*** shows a close-up of some of the design details that are possible.

Figure 4.10.3: Tooling with Cooling Channels
www.mmsonline.com

As discussed above and in *Section 3.4 – Rapid Tooling*, a major benefit of additively manufacturing devices that carry and transfer heat is the ability to create micro-scale and conformal cooling channels. This is a huge benefit for industrial tooling, especially for tooling that must handle heat, such as that for plastic injection molding, die casting, and various types of metal and ceramic molds (Altaf et al, 2013; Petrovic et al, 2011; Bobby & Singamneni, 2013) Tooling that contains internal cooling has better heat transfer performance, reduced cycle time to produce parts, a longer life, and better final part quality (Gibbons & Hansell, 2005; Rannar et al, 2007; Velnom & di Giuseppe, 2003). The device in ***Figure 4.10.3*** is a tool insert for molding golf balls that was additively manufactured; conformal cooling channels can be seen around the mold surface.

4.11. Acoustic Devices and Musical Instruments

When a sound wave strikes a surface, the surface either transmits, absorbs, or reflects that sound to the surroundings; the transmission, absorption, or reflection of the sound is determined by the acoustic properties of the object and its material (Setaki et al, 2012). Two types of devices are feasible to create with AM: acoustic absorbers and acoustic diffusers. The technology offers easily customizable geometry, tailored material properties, and the possibility of multi-material and multi-functional components, all of which can be utilized to create superior and custom acoustic absorbers and diffusers (Setaki et al, 2014; Godbold et al, 2007). In addition to custom absorbers and diffusers, additive technology can be used to create custom musical instruments.

Figure 4.11.1: Acoustic Absorber
Godbold et al, 2007

Figure 4.11.2: Acoustic Diffuser
diy3dprinting.blogspot.com

The purpose of acoustic absorbers is to reduce sound reflection from a surface. On the other hand, acoustic diffusers treat unwanted echoes and reflections by shattering the sound waves in many directions. While absorbers remove the sound waves, diffusers smooth them out by reflecting in many different directions. The physics of both types of devices are primarily driven by geometry, meaning that improvements in geometry will translate into improved performance. The use of additive technologies for the production of these devices would allow for very complex, theoretically-optimal shapes to be created without many of the classic manufacturing constraints, lead to a new generation of absorbers and diffusers with enhanced capabilities (Setaki et al, 2012 & 2014; Godbold et al, 2007). ***Figure 4.11.1*** shows an acoustic absorber, while ***Figure 4.11.2*** shows a diffuser, both of which were creating using AM.

Figure 4.11.3: Steampunk 3-D Printed Guitar
www.3ders.org

In the development of musical instruments it has traditionally been very important to carefully merge new technology with traditional designs, in order to preserve the essence of the instruments will allowing them to evolve and improve over time. There are three important considerations when designing and building musical instruments, namely design and aesthetics, playability, and sound quality. While it is possible to mass-produce decent musical instruments, the result will never be equal to customized instruments made by expert craftsmen. However, custom hand-made instruments are very costly and require a great deal of time, skill, and resources to produce. The use of AM to produce instruments can alleviate many of these problems. Instruments could be easily custom-made, with complex geometry to optimize the sound quality and designs to improve artistic appeal (Zoran et al 2012; Zoran, 2011). ***Figure 4.11.3*** shows the Steampunk guitar, which has the workings and sound quality of a Fender Telecaster with an additively manufactured body and functional details (Greengard, 2013).

4.12. Electronics and Batteries

Interest in the printing of electronic circuits has been growing in recent years as the demand for cheap, light-weight, and flexible electronics has grown. Such devices as roll-up displays, flexible keyboards, and printed-paper circuits offer many advantages over traditional plastic-and-wire circuits, including cost, ease of manufacture, flexibility, and good compatibility with a variety of operating conditions. Substrate materials such as paper-based and polymeric materials, as well as conductive ink, have been in development for many years (Das et al, 2011; Cummins & Desmulliez, 2012; Ahn et al, 2009). AM offers all of the advantages of traditionally printed electrical components, plus many more. The layered nature of AM allows for unprecedented design flexibility, the use of a huge variety of materials, the use several materials in a single part, the creation of structured and stacked electronics, and (most importantly), the embedding of electronics into components as they are being manufactured (Kim et al, 2009; Sarik et al, 2012; Lopes et al, 2012; Sterman et al, 2013).

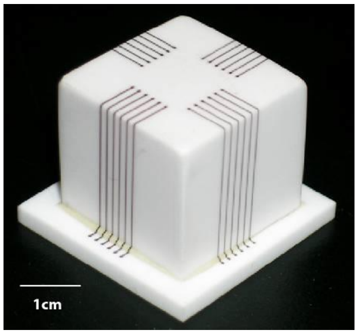

Figure 4.12.1: 3D Electrical Circuit King & Renn

For the actual printing of electrical circuits (versus embedding them into material), the most common process is aerosol jet printing. FDM and other processes are used sometimes as well, but do not have the flexibility and resolution for of aerosol printing (Sarik et al, 2012). Aerosol jetting is a variation of the material jetting process that uses an ink (metallic, polymer, ceramic, or dielectric) to print extremely fine details and tiny structures onto any surface, as seen in ***Figure 4.12.1*** (Hedges & Marin, 2012; Swiecinski et al, 2013; Mahajan et al, 2013; King & Renn; O'Reilly & Leal, 2010). ***Figure 4.12.2*** shows a sampling of electrical devices and circuits that were created using additive processes. Note that the LEDs, resistors, and other commercially produces devices were manually added later and were not printed with the circuit.

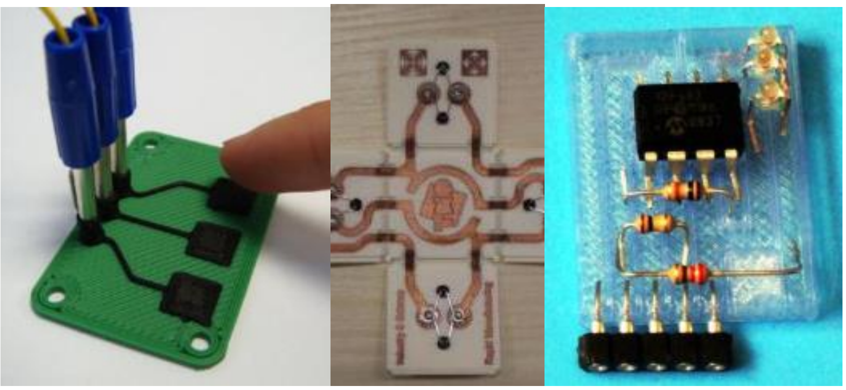

Figure 4.12.2: Additively Manufactured Electrical Circuits
www.core77.com, www.shapeways.com, www.3ders.org

A major reason to use AM for the production of electrical systems is the ability to physically embed them into the material. There are a number of design advantages to this, including the ability to create "smart" parts, the ability to better monitor the mechanics of the part (since the sensors are inside instead of on the surface), and the protection of sensors and electrical components from harsh environments. Examples of products where this would be beneficial are medical devices, structural components, and precision tooling (Siggard et al, 2006).

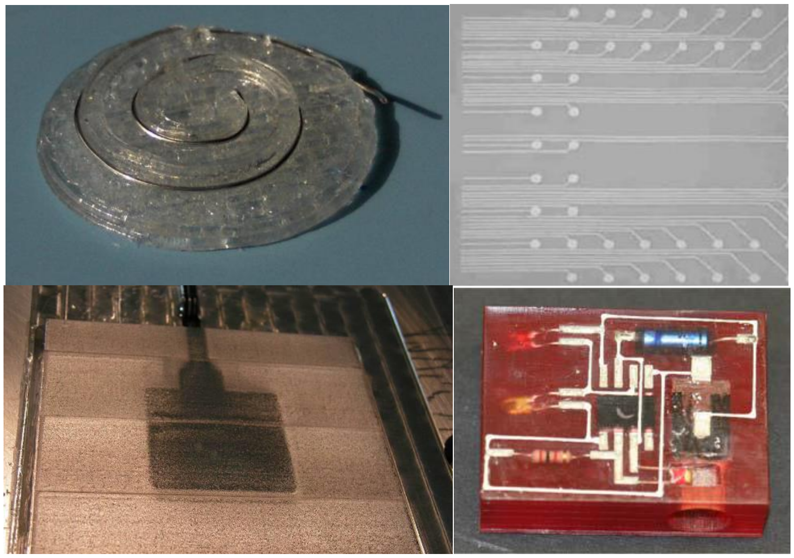

Figure 4.12.3: Items with Embedding Electronics Made by AM
Bayless et al, 2010, Zeng et al, 2006, Siggard et al, 2006, Lopes et al, 2012

There are a number of ways to create products with embedded electronics, including FDM, cladding, and ultrasonic consolidation. When FDM is used, the conductive material could be an extruded conductive material or wire that is printed or unrolled into the structure (Sarik et al, 2012; Kim et al, 2009; Bayless et al, 2010). Cladding is the fusion of (usually dissimilar) materials together into a composite material using wending, laser fusing, or other method (Black & Kohser, 2008, pg. 958). In the case of circuits, the process involves laser cladding of conductive pastes onto a surface, usually plastic, ceramic, or glass (Zeng et al, 2006; Sterman et al, 2013). Ultrasonic consolidation is another good method to embed the devices; since the process works at or near room temperature, it is possible to embed sensors, circuits, fiber optics, dielectric materials, and wiring into a full-density material without melting any of it. In aerosol jetting, FDM and cladding, the printing of the structure and electrical components occurred simultaneously with a single process, while in ultrasonic consolidation the (already built) electrical components are added manually where needed (Siggard et al, 2006). Some other processes that cannot easily handle conductive materials, such as stereolithography, can be used if integrated with a direct-write process like inkjet printing or aerosol jetting is used to build the electrical parts into the material while the structure is being created (Lopes et al, 2012). ***Figure 4.12.3*** shows embedded electronics or wiring in components made by FDM, cladding, ultrasonic consolidation, and stereolithography, respectively.

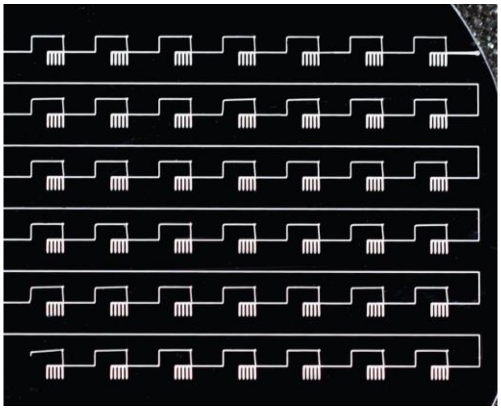

Figure 4.12.4: Tiny Printed Batteries in Process
Orcutt, 2014

The digital fabrication of electrical systems is an important step toward the creation of fully integrated functional devices (Lipson, 2005; Malone et al, 2008); another important milestone is the printing of batteries. The idea to print batteries and similar devices is not a new one; as discussed above direct-print electrical devices have been around for a while. Early attempts at printable power sources focused on direct-write technologies, solder printing, shape deposition manufacturing (a combination of material extrusion and CNC milling), and manual embedding of electronics into materials (Hayes & Cox, 1998; Malone et al, 2004 & 2008; Weiss et al, 1997). There are two major reasons to apply direct fabrication technology to the production of batteries, which are the technology's capability to produce very complex geometry and its ability to produce multi-material parts directly from the raw materials. These advantages allow for more compact and efficient designs, as well as provide the means to manufacture new and untested designs (Malone et al, 2008). A major goal is the miniaturization of batteries (Arnold et al, 2004) and other power sources (Pique et al, 2004) in order to improve designs and make possible new ones. This could make possible a whole new generation of technologies, such as self-powered biomedical sensors and fully integrated devices (Orcutt, 2014). ***Figure 4.12.4*** shows an array of tiny batteries in the process of being fabricated by researchers at Harvard University.

4.13. Prototyping and Concept Testing

The most obvious and well-known application of AM is the realization of models and prototypes. A prototype is defined as "working [physical] model [that] is constructed to permit full evaluation of a product" (Black & Kohser, 2008, pg. 199). The use of AM to create these is known as rapid prototyping, which is the creation of a model of some concept in order to test form, fit, or function or some combination of these (ASTM, 2012). While all of the basic AM processes can be used to rapidly prototype, the usually utilized processes are the more cost-effective ones like stereolithography, Polyjet, fused deposition modeling, sheet lamination, and selective laser sintering (Liou, 2008, pg. 243-293).

Product definition is the "process of translating customer needs into product design specifications," which is one of the most basic and important components of product design (Liou, 2008, pg. 5). There are a number of factors to consider for product definition, including

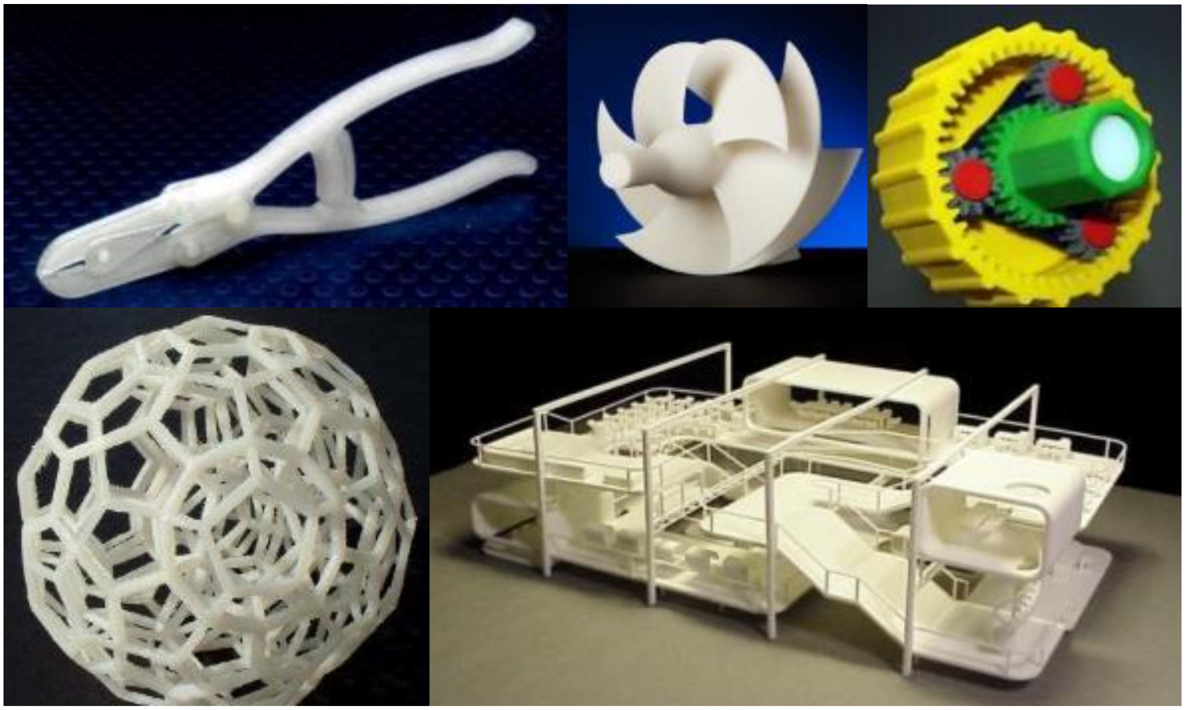

Figure 4.13.2: Examples of Rapid Prototypes
news.thomasnet.com, www.padtinc.com, www.trimechservices.com, www.georgehart.com, www.graphisoft-nordbayern.de

requirements definition, problem definition, conceptual design, design-for-assembly (DFA), design-for-manufacturability (DFM), and concept evaluation (Liou, 2008, pg. 4-7; Urbanic et al, 2013). Models are very important in keeping good communication between the designers and customers, to verify requirements, to justify decisions to management (Liou, 2008, pg. 19). In theory, the product definition and design are iterative and prototypes are very important in order to capture each phase and help guide further developments (Van Eijk et al, 2012; Black & Kohser, 2008, pg. 199).

Prototypes and physical models can be made a number of different ways, including with traditional manufacturing methods, such as milling, casting, or injection molding but this can become a very costly, complex, and expensive process (Gibson et al, 2010, pg. 8). Rapid prototyping relieves many of these burdens, allowing the creating of very good prototypes directly from a CAD model (Novakova-Marcincinova et al, 2012; Petrovic et al, 2011). ***Figure 4.13.1*** shows a sampling of prototypes created using additive processes. The major advantage of rapid prototyping is the ability to make functional models like the ones shown (Van Eijk et al, 2012; Novakova-Marcincinova et al, 2012; Petrovic et al, 2011).

4.14. Production Tooling Technology

The rapid manufacture of production tooling (also known as "rapid tooling") is one of the most promising and important application sectors for AM technologies. While the desired cast components can certainly be made directly using an additive process, this would be prohibitively expensive and slow for large-scale production. A better solution is to use a quick and cheap traditional process, such as injection molding or die casting, and to create the tooling quickly, cheaply, and efficiently using AM. The major advantages of using an additive process such as selective laser sintering or selective laser melting to create tooling are the ability to design and create complex and unique geometry (including cooling channels within the tooling), the ability to produce just one custom tool at a time, the small lead time, and the ability to create tooling on-demand (Gibson et al, 2010, pg. 370-371).

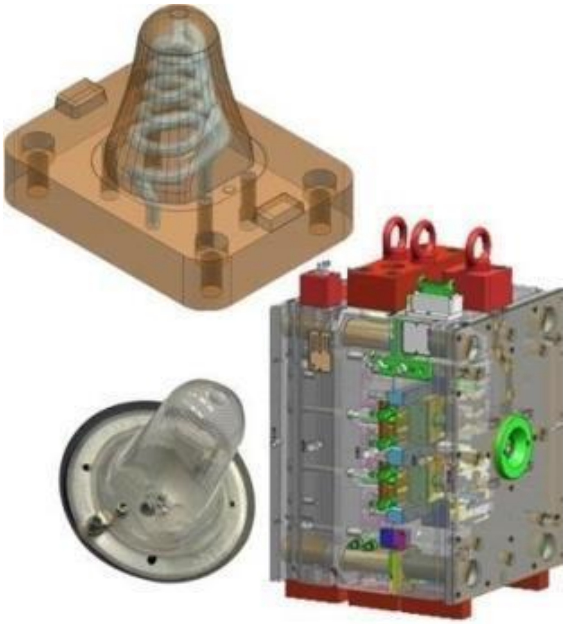

Figure 4.14.1: Injection Mold with Cooling Channels
www.nyp.edu

If the desired tools or molds are manufactured with an additive process, they may be created directly or a mold or pattern may be created to cast the tool later (Corcione et al, 2006; Abe et al, 2001). For the direct processes, an important capability is the creation of modular tooling and conformal cooling channels within the material of the tool. Modular tooling works like a typeset; some of the features are adjustable, depending on the needs of the application (Kerbrat et al, 2010). Dies for injection molding (Pessard et al, 2008; Dormal, 2003) and die casting (Pereira et al, 2012) is a common and important use. Tools and molds with internal cooling (***Figure 4.14.1***) have better performance, resulting in a reduction of part cycle time and improvement of final part quality due to reduced thermal distortion (Rannar et al, 2007; Velnom & di Giuseppe, 2003). If it is desired to create a mold or die for future tool making, there are a number of ways to do this with AM techniques (Corcione et al, 2006; Bassoli, 2007; Gebhardt, 2012, pg. 47-51; Black & Kohser, 2008, pg. 263 & 276-277), either directly or by creating a master or prototype that will be used in investment, lost foam, or lost wax casting of the tooling (Bassoli et al, 2007; Sun et al, 1989).

4.15. Expendable-Mold Casting Technology

In addition to the ability to aid in the production of tooling, such as permanent molds and dies, AM can be applied to foundry technology, particularly expendable-mold casting. Expendable-mold casting techniques are the "typical" casting methods, usually sand casting, shell casting, investment casting, and lost-foam casting (Black & Kohser, 2008, pg. 263).

In sand casting, a master part is created and refractory sand (usually mixed with water or clay) is packed around it until the mold material is hard. Once the mold is stabilized, the master part is removed, leaving a cavity in the shape of the desired casting. Typically, the mold will be made in two parts and will form the full mold when joined together. Usually the molds are destroyed or damaged in the process of the casting, necessitating the creation of a new mold for each casting (Black and Kohser, 2008, pg. 283-285; Gebhardt, 2012, pg. 85). Shell casting is similar in principle to sand casting, except that the grains are coated with a thermoplastic resin and the master part is heated to partially cure the resin on contact and join the particles together into a solid mold. The hot master part is then removed and the partially-cured shell is baked in an oven to complete the curing (Black and Kohser, 2008, pg. 295-296). ***Figure 4.15.1*** shows a sand mold and ***Figure 4.15.2*** shows a shell mold, both with master parts during the creation of the molds.

Figure 4.15.1: Sand Casting and Master
www.rcoutboard.com

In both investment casting and lost-foam casting, an expendable master part is required to make each casting, as the masters are lost in the casting process unlike sand and shell casting. Investment casting begins with the creation of a master part out of wax, nylon, aluminum, or any other material that is easy to work with and has a good surface finish and (relatively) low melting point. The master is dipped repeatedly into a slurry bath to build up layers of hard ceramic material until the desired thickness of the mold is achieved. ***Figure 4.15.3*** shows a wax investment casting master next to a finished mold. The whole thing is then placed into an oven to melt and burn out all traces of the master part, leaving an excellent shell mold (Black and Kohser, pg.

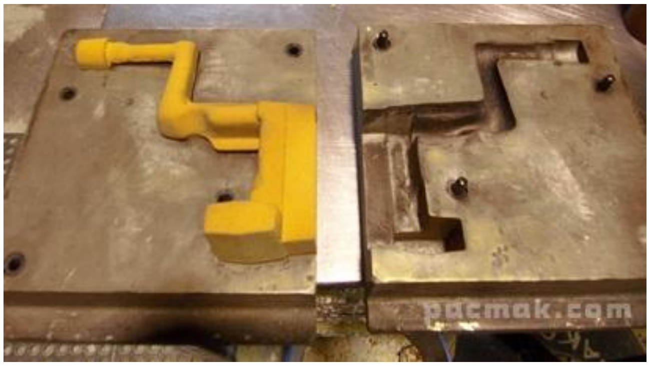

Figure 4.15.2: Shell Casting with Master
www.pacmak.com

305-306; Bassoli et al, 2007; Prasad, 2012; Sun et al, 1989; Pham & Dimov, 2001, pg. 125; Gebhardt, 2012, pg. 85). Lost foam casting is similar to sand casting, except the master part is made from a soft plastic or foam (such as in ***Figure 4.15.4***) and is not removed from the mold prior to the pouring. The master is consumed, burned away, and replaced by the molten material (Black and Kohser, 2008, pg. 308-309).

Figure 4.15.4: Lost Foam Casting and Master
www.jmt.in

Figure 4.15.3: Investment Casting and Master
www.stellite.de

AM can be applied to this field of casting in two ways; the direct manufacture of the molds and the production of metal or soft master parts are the ways that it can be used. For the direct creation of the molds, the stereolithography, binder jetting, FDM and the laser sintering processes are the most commonly used ones (Corcione et al, 2006; Bassoli, 2007; Wang, 2010, pg. 57). ***Figure 4.15.5*** shows a directly-printed mold. When creating masters for expendable-mold casting, high accuracy and good surface finish are required but high strength is not a priority. The patterns can be made from metal, plastic, wax, nylon, or other materials by stereolithography, laminate layer manufacturing, and laser sintering, depending upon the application and the casting technique used (Bassoli et al, 2007; Sun et al, 1989; Pham & Dimov, 2001, pg. 92; Harrison, 2001, pg. 96-97).

The masters for both sand casting and shell casting can be actual metal or ceramic master parts, with fully formed surfaces and production-quality finishes (Gebhardt, 2012, pg. 17-18 & 20-21). Since these parts are not damaged or consumed in the process of creating the mold and will be used to make hundreds or thousands of molds, it is worth the extra effort to create a perfect master part to form the mold. The more accurate and fine AM processes, such as sintering, should be used to create these master parts (Gebhardt, 2012, pg. 20-21; Redden, 2001, pg. 115-118; Gebhardt, 2012, pg. 86-87).

Investment casting masters are hard parts with relatively low melting points made with good accuracy and surface finish. AM techniques are useful in creating these, particularly stereolithography, material extrusion, sheet lamination, and powder bed fusion processes (Wang, 2010, pg 59-66; Gebhardt, 2012, pg. 88). In lost foam casting, a foam or light plastic (such as polystyrene) master is needed. When manufacturing the masters in small quantities, they can be made by hand or cut with a machine (Brooks & Aitchison, 2010; Black and Kohser, 2008, pg. 308-310). When many are needed or when they need to be very fine and consistent they can be injection molded or

Figure 4.15.5: 3-D Printed Mold
proto3000.com

additively manufactured. While molding is faster, once the tooling is created, the additive process gives more flexibility, allows small design modifications and saves the cost and lead time of the tooling. The castings are infinitely customizable due to the properties of AM (Bassoli et al, 2007; Chhabra & Singh, 2011).

4.16. Construction Technology

The construction of buildings is an expensive and labor- and time-consuming business. There has been a big push in recent years to bring automation to the construction industry in order to reduce the time and labor, and eventually the cost, of construction. There are a number of proposed solutions, including mass-produced panels for modular building, concrete spraying, robotic assembly of buildings, and additive technologies. Freeform fabrication is the ultimate automation of construction, as no pre-construction or materials processing are needed and the fabrication is done in-place without geometric restrictions and from a single machine (Bonwetsch, 2012; Lim et at, 2012; Buswell et al, 2007 & 2008; Pegna, 1997). There are three important types of additive methods that can be applied to construction technology, namely contour crafting (Khoshevis, 2004), D-Shape (Kidman, 2009), and concrete printing (Le et al, 2012). All three are based on various common additive processes and each has its own set of applicable materials and appropriate uses (Lim et al, 2012).

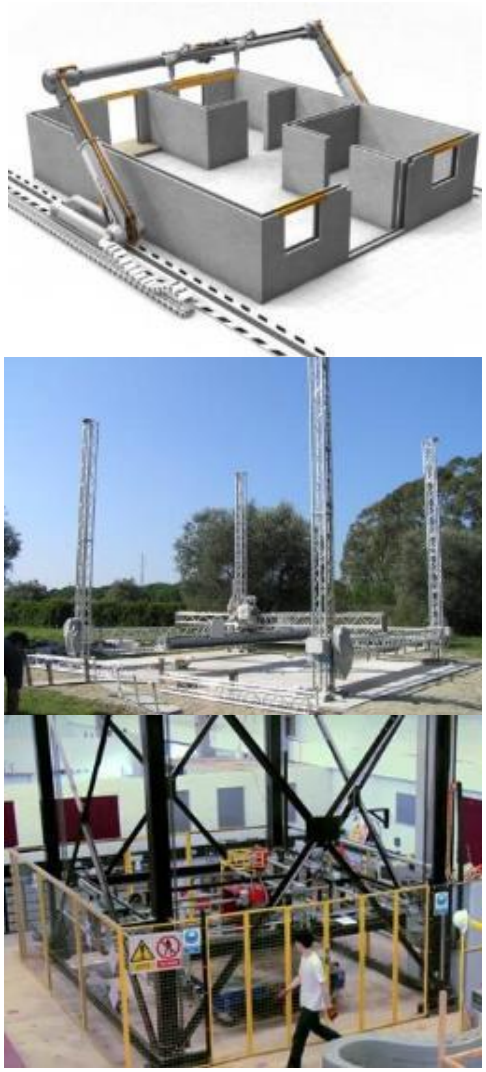

Figure 4.16.1: Additive Construction Machines
readwrite.com, tpuc.org, blog.ponoko.com

The contour crafting process is the oldest and best-developed of the three additive construction processes. The machine consists of a large computer controlled gantry, crane, or robotic arm to which an extruder head is attached. Chemically-activated concrete is the usual material and it is extruded FDM-style out against a trowel in order to form particular geometry. The major advantages of contour crafting are the minimization of material use, the smooth surface finish, the structural design freedoms, and the ability to use multiple materials to embed plumbing, electrical, and other components into the structure as it is being printed (Khoshevis, 2004; Bosscher et al, 2007; Lim et al, 2012; Zhang & Khoshevis, 2013; Yeh & Khoshevis, 2009). The top picture in ***Figure 4.16.1*** shows an artist's rendering of a whole contour crafting rig in operation. D-Shape is an interesting variation of the binder jetting process on a much larger scale and without the standard powder bed. A powdered sand or concrete is the raw material and it is selectively hardened by a binder material that is jetted into the powder where needed. The powder for each layer of the build is deposited by spraying and compacting, not rolling like in 3DP. ***Figure 4.16.1*** shows a D-Shape machine in action in the center picture; it is visually similar to a 3DP machine (Kidman, 2009; Lim et al, 2012). Concrete printing is very similar to contour crafting, except the resolution of the extruded material is much finer and the machine works like a very large hobby 3-D printer (Lim et al, 2012; Le et al, 2012). The bottom picture in ***Figure 4.16.1*** is of a concrete printing machine. ***Figure 4.16.2*** shows samples of product made by each of the three processes.

Figure 4.16.2: Products Made by Contour Crafting, D-Shape, and Concrete Printing
www.dailymail.co.uk, openmaterials.org, blog.ponoko.com

A major future application of the direct digital construction of structures of virtually any shape and large size is the construction of lunar habitats, using the local soil as the raw material. Two options are available to build structures for extraterrestrial settlements: either transport all of the building material, equipment, and personnel from Earth or find a way to fabricate the building in-situ. Until the advent of additive building processes, the technology did not exist to practically utilize the second option (Khoshevis, 2014; Benaroya & Bernold, 2007; Gruber et al, 2007). Some of the processes that can be used to create structures and building materials from extraterrestrial soil are the D-Shape process (Cesaretti et al, 2014), the contour crafting (Khoshevis et al, 2005 & 2013), and laser powder deposition (Balla et al, 2012). ***Figure 4.16.3*** shows an artist's conception of the printing of a lunar base by NASA using a contour crafting process.

Figure 4.16.3: Lunar Contour Crafting
www.youngmarketing.co

4.17. Architecture and Construction Design

Architecture is one of the oldest of the technical professions and the communication of ideas has always been somewhat of a difficulty, necessitating the creation of models. These models are an important part of validating and communicating ideas for any product, but especially large and expensive construction projects. The basic design work for an architectural project these days is done with 3-D modeling software; while a digital model could be sufficient for the designer, a physical and functional model is required for communication with customers and managers. Traditionally, the creation of these models had to be done one at a time by a skilled and well-trained artist, a process which could take a long time and be very costly (Overy, 2001, pg. 227-229; Pignataro et al, 2014; Gebhardt, 2012, pg. 93; Ryder et al, 2002).

Rapid prototyping techniques allow the direct fabrication of a 3-D model directly from the digital model, saving a huge amount of time and resources that would be consumed if the models were made by hand (Novakova-Marcincinova et al, 2012; Ryder et al, 2002; Overy, 2001, pg. 227-229). Some complex and detailed aspects of the project that can easily be created on the final structure may be difficult or impossible to create on a prototype using a traditional process; the greater detail of additively manufactured models helps to eliminate this problem, allowing a higher-fidelity model to be created (Overy, 2001, pg. 227-229; Gebhardt, 2012, pg. 93). ***Figure 4.17.1*** shows examples of architectural prototypes that were created by AM. The left and center figures were created by FDM, while the model on the right was made using a laminate process.

Figure 4.17.1: 3-D Printed Architectural Models
gfxspeak.com, www.stratasys.com, www.mcortechnologies.com

4.18. Composite Materials Technology

A composite material is a solid that consists of two or more distinct materials which have significantly different physical properties, bound together mechanically or metallurgically to create a new material that has different properties than any of the individual constituent materials. The various materials remain distinct within the composite and interfaces exist between each of the material zones in the composite. The typical reasons to use composite materials are to create specialized or customized material, to reduce cost, and to reduce weight. There are three types of composite materials: laminar composites, particulate composites, and fiber-reinforced composites (Black and Kohser, 2008, pg. 182-188).

Laminar composites are built of distinct layers of material joined together and include things such as plywood, coatings, claddings, laminates, and bimetallics. These materials are typically used when reduced cost, increased durability, enhanced electrical properties, customized expansion properties, lighter weight, improved strength, and improved appearance are desired (Black and Kohser, 2008, pg. 183). It is very easy to apply AM to these usages, as the construction process is simple layering. Laminated object manufacturing (for non-metals) and ultrasonic consolidation (for metals) are the most common methods (Windsheimer et al 2007; Weisensel et al, 2004; Hahnlen & Dapino, 2014; Obielodan & Stucker, 2014), but powder deposition (Feng et al, 2012; Emamian et al, 2010 & 2012; Lipke et al, 2010; Gu et al, 2012;

Song & Park, 2006), fused deposition modeling (Nikzad et al, 2011; Ilardo & Williams, 2010; Kalita et al, 2003), and laser sintering (Clair et al, 2008; Zeng et al, 2012) are also widely used. ***Figure 4.18.1*** shows a laminar composite material.

Figure 4.18.1: Laminar Composite Material www.archiexpo.com

The second type of composite material is the particulate composite, which consists of discrete particles of a material surrounded by a matrix of a second material. This type of composites includes concrete, asphalt, and multi-component power metallurgy processes. Usually two materials are used that have very different melting points, where the material that will be the matrix has the lower one; in the case of powder, the two particulate materials are mixed together and heated until the matrix material melts and locks in the second material (unlike alloying, where both materials are melted). The typical reasons to use this type of composite are to increase strength and customize properties (Black and Kohser, 2008, pg. 184-185). AM techniques are very applicable to creating these materials, due to its ability to build in layers and control the melt properties. The most common processes used are selective laser sintering and powder deposition, which has been used to create ceramic materials and metal-matrix composites. The power of the laser is set to be sufficient to melt the matrix material, but not the added material (Gu et al, 2012). Examples of ceramic composites that have been additively manufactured include polyamides (Deckers et al, 2012; Bassoli et al, 2012; Krznar & Dolinsek, 2010), nylon-silica (Chung & Das, 2008), cements (Gibbons et al, 2010), silicon-carbide (Stevinson et al, 2006 & 2008), glass-hydroxyapatite (Winkel et al, 2012), and aluminum oxide-polystyrene (Zheng et al, 2006). Example of metals used in metal-matrix composites are Inconel (Cooper et al, 2013), other nickels, titanium, iron, and aluminum (Gu et al, 2012). ***Figure 4.18.2*** shows the structure of an Inconel-titanium carbide composite created by laser powder deposition; the grains of metal in the melted matrix are clearly visible.

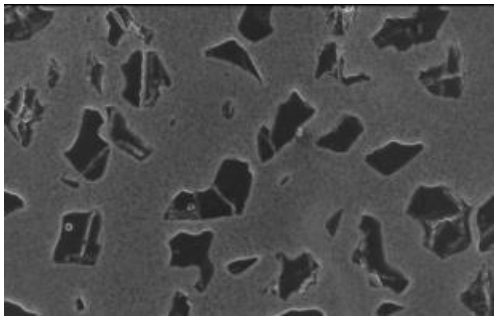

Figure 4.18.2: Particulate Composite Material www.lia.org

The most popular and common type of composite material is the fiber-reinforced composite, where thin fibers of a strong and stiff material are embedded into a matrix of the other, allowing a sharing of the load on the material; the fibers accept most of the weight and provide stiffness, while the matrix supports and transmits forces to the fibers, offers them protection from harsh environments, and provide toughness This is usually done to increase the strength, stiffness, fatigue resistance, and strength-to-weight ratio of the whole material (Black & Kohser, 2008, pg. 185). The procedure for additively manufacturing fiber-reinforced composites is similar to that of particulate composites, except that the non-melting material is in the form of fibers, typically carbon fibers. The most common additive processes used are FDM (Duty,

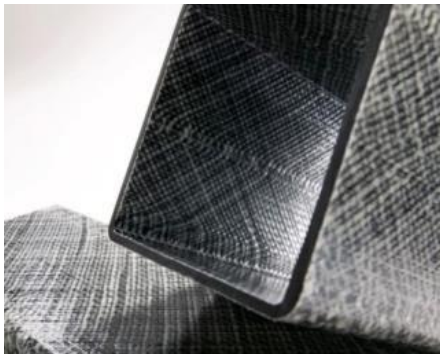

Figure 4.18.3: Fiber-Plastic Composite www.directindustry.com

2012; Rice et al, 2011) and SLS (Rice et al, 2011). These threads can be mixed into ceramics materials, such as polyamides (Goodridge et al, 2011; Salmoria et al, 2011), plastics (Ilardo & Williams, 2010), metals, and polymers (Rice et al, 2011) in order to create fiber composite materials. ***Figure 4.18.3*** shows an example of a fiber-reinforced plastic structure component.

4.19. Spare Parts Industry

An important factor in sales and production these days is the logistics and acquisition of spare parts, particularly in industries that utilize highly automated, complex, and linked machinery. It is inevitable that components on these machines will eventually fail, putting a machine or a whole production line out of commission until the deceased component is replaced. The effects of this will be seen in the production capacity, which affects the profitability of the plant or company. The company has to correctly choose the correct spare parts to keep in the factory at any time. If too many or the wrong ones are bought, money and storage space are wasted and there is the risk that the parts will be obsolete by the time they are finally used; however, if not enough of the needed parts are in stock, they must be special ordered, causing plant downtime and loss of productivity as the parts are manufactured or shipped from a warehouse (Rommel & Fischer, 2013).

The major advantage of using AM to produce spare parts is its ability to produce customized parts on-demand, without any special tooling. At some point in the future, as the processes improve and become more cost effective, the on-demand manufacture of spare parts in each production facility could become a reality. However, for now, it is only practical for dedicated spare parts manufacturers to maintain the extra machines and personnel to run them (Khajavi et al, 2014; Rommel & Fischer, 2013). There are two possible ways to do this, depending on the situation. The first is to keep a very small stock on hand to meet emergencies and let customer demand trigger the production of more stock. This will allow immediate delivery of emergency parts while expediting larger quantities; however, storage space is required for the stock of parts kept on hand. The second idea is to additively manufacture all the of the parts as they are ordered; this is slower than the first model, but still much faster than traditional manufacturing the parts and does not require the holding of any parts. Regardless of which model is used, it is obvious that additively manufacturing spare parts will improve the throughput of parts and improve the logistics of getting spare parts to production facilities and others who require these

Figure 4.19.1: Additively Manufactured Aircraft Parts
www.ipmd.net, www.arcam.com, www.geaviation.com

items, such as aircraft spare part suppliers (Rommel & Fischer, 2013; Holmstrom et al, 2010; Khajavi et al, 2014; Walter et al, 2004). Additively manufacturing the spare parts will clearly cost more than making them by a tradition method; however, the on-demand nature of the printing, the speed of production, and the customizability can offset this easily (Holmstrom et al, 2010). ***Figure 4.19.1*** shows examples of additively manufactured spare parts for use on aircraft.

4.20. Textiles, Clothing, and Shoes

The manufacture of textiles is one of the oldest production industries and the application of AM to it is a new and interesting concept. While it currently is too expensive and complex to ever replace conventional fiber-based cloth production, there are some niche markets that could benefit greatly from the technology, particularly high-performance textiles and "smart" cloth (Bingham et al, 2007). High-performance textiles are ones that are special properties, such as high strength, breathability, or stab resistance. They have special functionality that is added to it by processing, materials, finishing, composition, or construction. Examples of high-performance textiles are Kevlar and Gore-Tex (Cherenack & Van Pieterson, 2012; Bingham et al, 2007; Johnson et al, 2013). In contrast, smart textiles are designed to sense surrounding conditions and have the inherent ability to adapt to these conditions within the textile structure itself. This typically involved the integration of electronic devices into conventional fabrics. A good application for smart textiles is equipment and clothing for emergency responders (Van Langenhove & Hertleer, 2004; Cherenack & Van Pieterson, 2012; Budelmann & Krieg-Bruckner, 2012; Curone et al, 2010).

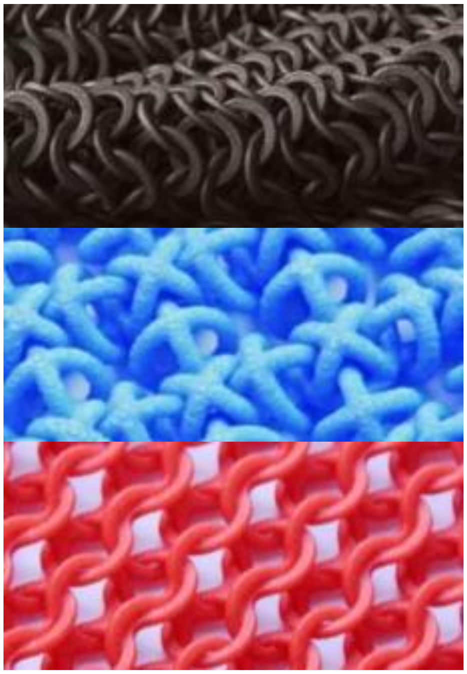

Figure 4.20.1: 3-D Printed Textile Patterns
www.architerials.com

There are a number of different types of textiles, including traditional fiber-based ones that are made by weaving or knitting, and sheets of small linked assemblies similar to chainmail. Both types can, in theory, be created using additive processes but the current trend is to develop the chainmail-type fabrics for AM; they are easier to model, easier to create, and have far more applications than old fiber-type textiles (Bingham et al, 2007; Bingham & Hague, 2013). ***Figure 4.20.1*** shows some of the textile geometry that is possible with AM.

The major reason to use additive processes for the production of textiles is the ability to create the micro-level or meso-level free-moving assemblies of small links in a single manufacturing process, opening the door to significant improvements in complexity, design freedom, and functionality of textiles over traditional fiber-based textiles. The design freedom will allow the creation of new and specially-tailored hybrid textiles for a huge number of new and current applications, including sportswear. Additively manufacturing textiles will allow for the manufacture of fully-functional net-shape clothes in new designs ***(Figure 4.20.2)***, the design of new high-tech smart textiles with circuitry and sensors built in, and the possibility of designing cloth with adjustable physical properties (Bingham et al, 2007; Bingham & Hague, 2013;

Figure 4.20.2: 3-D Printed Clothing
mocoloco.com, cubify.com

Chowdhury et al, 2012; Rocha, 2013). Another interesting possibility with the technology is the 3-D scanning of existing textile articles, which will then be additively manufactured using customized geometry and materials (Ukita & Kanade, 2012; Bingham & Hague, 2013).

AM technologies are also very applicable to the design and fabrication of customized footwear. Rapidly evolving customer preferences and needs in this industry has led to high competition among footwear designers to bring new products to market quickly. Additive technologies can be utilized for both prototyping and manufacturing of these customized shoes, reducing costs and time to market over traditional methods. Prototyping is important for footwear, as many manufactures seek and present scientific validity to their claims of product improvements and features; studies can be done in advance of production on prototypes instead of the real products, giving a scheduling and economic edge.

In addition to the advantages of prototyping footwear, the design freedom, freedom from expensive fixed tooling, the ability to handle a huge variety of materials, the ability to create functionally-graded components, and the almost infinite customizability of additive manufacturing processes opens the door to completely new and completely personalized footwear designs (Manoharan et al, 2013; Telfer et al, 2012). This personalization is important, as it improves fit and performance of the shoes, reduces the risk of injury, and is healthier for the user (Salles & Gyi, 2012; Telfer et al, 2012; Sun et al, 2009). ***Figure 4.20.3*** shows three examples of additively manufactured footwear; the left and center pictures are fancy customized evening shoes and the right picture is a sports shoe that has been customized for the user.

Figure 4.20.3: 3-D Printed Footwear
www.solidsmack.com, www.additivefashion.com, www.3ders.org

4.21. Jewelry

The successful design, development and manufacture of jewelry products often involve the design and production of very complex and personalized geometries. Traditionally, there was a number of ways to accomplish this, including investment casting (Ott & Raub, 1985) and carving with hand tools; in spite of thousands of years of technique development, however, even the most skilled artisans are not able to create some of the most complex geometric shapes, such as those based on fractals, repeating patterns, and mathematical formulas. There are two core benefits to using AM in the design and production of jewelry: these are the staggering design freedom, both for direct manufacture and the creation of casting masters, and the ability to create good and cheap prototypes of the products before manufacture, in order to increase communication between the artist and the customer (De Beer et al, 2012; Hohkraut, 2010). ***Figure 4.21.1*** shows several examples of jewelry prototypes made by AM. From a design and production viewpoint, there are two categories of jewelry: precious jewelry and costume jewelry. Regardless of the material used, the precious jewelry is individualized, extremely high quality, and is created as a piece of art, while costume jewelry is mass-produced or made in batches and design focuses on creativity and quick time-to-market. The huge design freedom of AM technologies allows the customization and "art quality" of precious jewelry to be integrated with the quick production and creativity of costume jewelry, improving the quality and reducing the production cost of both products. Instead of commissioning an experienced, and expensive, artist to create precious jewelry, users can now design their own with CAD software and hire anyone with the competent equipment to create it quickly and cost effectively (Gausemeier, 2011; Hohkraut, 2010; MacLachlan, 2014). There are many specific applications of additive technologies to the production of jewelry, including the production of cores for investment casting, the creation of complex and customized individual products, the formation of unusual alloys of precious metals

Figure 4.21.1: Prototype Jewelry made by AM
www.additive3d.com

Figure 4.21.2: Additively Manufactured Jewelry
dailyjewel.blogspot.com, Projet, 2013, www.fabricatingandmetalworking.com

for jewelry use, the production of titanium and alumide jewelry, and the manufacture of sintered-metal jewelry (Gausemeier, 2011; Projet, 2013; Paiva et al, 2012; De Beer et al, 2012; Fischer-Buhner, 2012). ***Figure 4.21.2*** shows three examples of rapidly manufactured jewelry; the left and center figures was created by investment casting and polishing, while the right one was created directly by a sintering process.

4.22. Ceramics Technology

Ceramics are compounds of metallic and non-metallic elements that exist in a variety of forms and compositions, typically in the form of oxides, carbides, and nitrides. Most ceramics have a crystalline structure like metal but the chemical bonds are strong ionic or covalent bonds, giving the material high hardness, brittleness, a high melting point, low thermal and electrical conductivity, low thermal expansion, good material stability, high elastic modulus, good creep resistance, and high compressive strength; generally, ceramics retain their properties at elevated temperatures. Some of the most common applications of ceramics materials include whiteware (such as clay pots, pipes, and bathtubs), refractory materials (such as casting sand), abrasives, electrical and magnetic components (such as resistors, superconductors, and super magnets), glasses, cermets (such as brake pads), cements (such as plaster and concrete), and protective coatings (such as enamel) (Black & Kohser, 2008, pg. 175-180). ***Figure 4.22.1*** shows some commonly used ceramic products.

The application of AM to the fabrication of ceramic products is a very important development of the technology, as it removes many of the problems and restrictions that have traditionally plague the ceramics industry. Such things as shrinkage during production, the need for specialized tooling, and the low material yield have always impeded the industrial utilization of these important and useful materials. The layer-by-layer build style of additive processes almost eliminate the shrinking and cracking problems, there is no special tooling of any kind required for AM, and the processes are fast, accurate, relatively cost effective, and produce little-to-no waste; in addition, AM offers much design freedom and allows easily customizable material compositions and properties. The most common additive processes used to manufacture ceramics are the binder jetting process and the material jetting (inkjet printing) process, but sheet lamination (LOM), powder bed fusion (SLS/SLM), material extrusion (FDM), and vat polymerization (SLA) are also used for various applications. The use of additive technologies has improved many existing technologies and opened up new ones (Shulman et al, 2012; Hagedorn et al, 2010; Yoo et al, 1993; Diegel et al, 2012; Zhang et al, 1999).

Figure 4.22.1: Common Ceramic Items
www.autoanything.com, groutrescuect.com, www.zorotools.com, en.wikipedia.org

Binder and material jetting are the processes normally employed for the printing of ceramics. As the process involved the direct printing of binder material into a powder bed or the inkjet printing of powder and binder together, these are the simplest and fastest ways to directly fabricate ceramic materials. The level of refinement in the processes is such that it is possible to print very find geometry, as well as structural-quality products (Yoo et al, 1993; Lejeune et al, 2009; Zhao et al, 2002). The binder could be a variety of products, including epoxies and even water (Ozkol, 2013; Vorndran et al, 2008 & 2011). A huge variety of powders can be used, depending on the desired properties; some examples include farringtonite (Vorndran et al, 2011), alumina (Maleksaeedi et al, 2014), clay (Diegel et al, 2012), lead zirconate titanate (PZT) (Wang & Derby, 2005), and hydroxyapatite, dicalcium phosphate, and calcium polyphosphate for biomedical applications (Suwanprateeb et al, 2010; Seitz et al, 2005; Gbureck et al, 2007; Shanjani et al, 2011). ***Figure 4.22.2*** shows an example of a ceramic product created by 3DP after post-processing.

While there have been challenges in the development, the FDM process can be modified to work with slurries and powder-in-wax or powder-in-binder, giving good surface finish and decent tolerances. The parts can be printed to spec, then fired or cured to full density and strength, similar to traditional ceramic manufacturing methods. Some of the materials that can be printed this way include alumina, zirconia, clay, PZT, various types of ceramic fibers, and polymer-ceramics materials (Shulman et al, 2012; Kalita et al, 2003; Bamford, 2011). An FDM-created ceramic piece of art is shown in ***Figure 4.22.3***.

Figure 4.22.2: Ceramic Vase by 3DP
www.ponoko.com

Figure 4.22.3: Ceramic Art by FDM
www.3ders.org

Of the many powder bed fusion processes, the ones typically utilized are the selective laser sintering (SLS) and selective laser melting (SLM) processes. Unlike metals, ceramic parts made by powder bed fusion are usually "green" parts and require additional processing before they reach full density and strength, as the ceramics (such as alumina-zirconium) generally have extreme melting points (Glazer et al, 1993; Shishkovsky et al, 2007; Hagedorn et al, 2010; Wang & Derby, 2005). Two major advantages of using the SLS process is the possibility of customizing the properties, including electrical and thermal properties, and of producing extremely fine geometry, including cellular geometry (Chen et al, 2005; Agarwala et al, 1993; Regenfuss et al, 2007 & 2008; Stampfl et al, 2004). One of the common uses for SLS-made ceramics is the creation of scaffolds for biotechnology applications (Chen et al, 2006). An example of a ceramic object made by SLS is shown in ***Figure 4.22.4***.

The sheet lamination process was originally intended for the manufacture of plastic or paper prototypes, but the process works quite well with green ceramic tapes; these can be precision cut with a blade or laser, stacked, fused, and fired to produce extremely fine details and good tolerances (Shulman et al, 2012). Vat polymerization can also be used to create ceramic materials, by loading the photopolymer with ceramic powder. Some of the powders that are used include alumina (Zhang et al, 1999; Bertsch et al, 2004), PZT (Cheverton et al, 2012), and barium titanate (Jang et al, 2000). The micro-scale devices shown in ***Figure 4.22.5*** were created by stereolithography using a ceramic-impregnated resin.

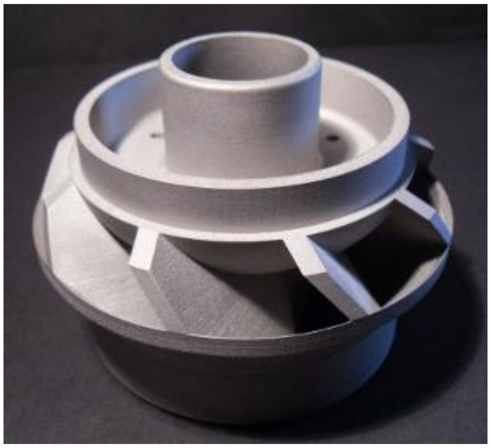

Figure 4.22.4: Ceramic Part by SLS
www.dentalcompare.com

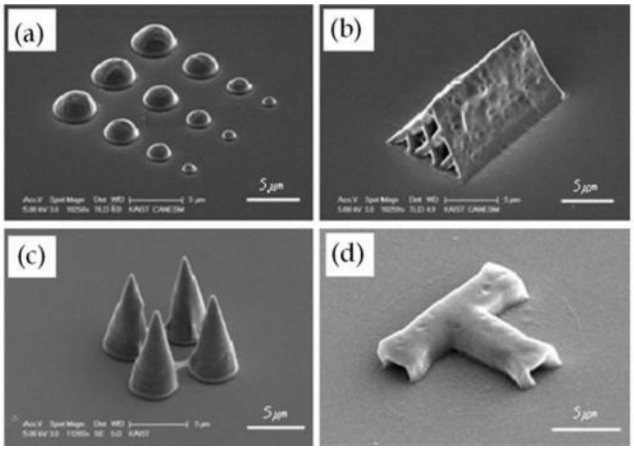

Figure 4.22.5: Microceramic Parts by SLA
www.intechopen.com

4.23. Food Industry

The use of edible materials in AM processes is new and interesting concept has several important developments, both for the custom food industry and for the development of additive technologies. First, it offers additive technologies to the custom food industry for the production of complex items with intricate geometries, customizable textures and designed nutritional contents. It also presents a low-cost, simple, and non-toxic method for children to learn how to use and experiment with additive technologies. Finally, food matter with appropriate properties can be used as cheap, sacrificial, bio-degradable, bio-compatible, or recyclable support and prototyping material for more tradition additive processes (Wegrzyn et al, 2012; Periard et al, 2007; Southerland et al, 2011; Sereno et al, 2012). Food printing machines typically use an extrusion-based or powder-based design and the only restrictions on the material are that it must

Figure 4.23.1: 3-D Printed Food Items
spectrum.ieee.org, www.3ders.org, chocolateprinter.wordpress.com

be able to be moved through a syringe or be available in a meltable powder, such as cake frosting, liquefied cheese, molten chocolate, marshmallow, peanut butter, white sugar, meat paste, and pasta dough (Cohen et al, 2009; Zimmerman et al, 2012; Wegrzyn et al, 2012; Hao et al, 2010; Periard et al, 2007; Southerland et al, 2011; Lipton et al, 2010). ***Figure 4.23.1*** shows a food printing machine and some 3-D printed food items.

4.24. Toys and Hobbies

While toys and scale models are usually considered consumer goods, it should be discussed separately because the customer needs are very different for toys than for other consumer goods. From the AM point of view, "toys" includes both playthings for children and hobby models of airplanes, ships, and such models. While children's toys are an important commodity, the hobby models are where the greatest benefits can be gained from utilizing additive technologies. While most consumer goods require good physical properties and durability, hobby models require very fine details and accurate scaling without too much concern for physical properties. Some of the processes that can be used to produce these are fused deposition modeling (FDM), laminated object manufacturing (LOM), and stereolithography (SLA) (Gebhardt, 2012, pg. 82; Wargaming). ***Figure 4.24.1*** shows a model tractor made by FDM.

Figure 4.24.1: 3-D Printed Model Tractor
www.thesun.co.uk

4.25. Archaeology and History

The discovery, preservation, and continuation of cultural heritage is something important to all humans and is a topic of major research throughout the world. This can take many forms, two of which are the science of archaeology and the study of art and other cultural artefacts. The use of digital technologies has much promise to contribute to this and even improve the efficiency and quality of the work (Zhang et al, 2012). In particular, the use of AM technologies offers three major capabilities to the field of cultural preservation, namely modeling, preservation, and restoration.

The ability to quickly and easily construct complex and accurate models is a very important reason to utilize additive technologies, both for day-to-day handling and for preservation. With the advent of 3-D scanning technologies, the production of good solid models is just a click of a button away. This is particularly important for the preservation of skulls, bones, priceless art, mummies, and wood objects such as ships (Fantini et al, 2008; Zhang et al, 2007; Almeida et al, 2007; Soe et al, 2012; Steele & Williams, 2003; Bandiera et al, 2013). These items need to be measured, studied, modeled, and displayed in order for any benefit to come from their discovery, but repeated handling will likely damage or destroy the relics and good models are difficult and costly to make by hand. One solution to this problem is the additive manufacture of an accurate model for every day handling and for public display, so that the pieces can be studied accurately, discussed, and enjoyed without contact and risk for damage (Lontos et al, 2012; Zhang et al, 2014; Tucci & Bonora, 2011; Bouzakis et al, 2008; Fantini et al, 2008; Thilmany, 2012; Replica, 2014). ***Figure 4.25.1*** shows some excellent models of ancient Chinese art that were created by digital scanning and AM techniques.

Figure 4.25.1: Additively Manufactured Models of Chinese Art
Zhang et al, 2012

Another important and useful application for 3-D technologies such as digital scanning and AM is the restoration of broken or damaged historical and artistic finds, such as religious art and buried ship timbers. The remaining parts can be scanned and digitally reassembled, allowing for a quicker, more accurate, and more complete restoration (Arbace et al, 2013; Soe et al, 2012; Zhang et al, 2007; Almeida et al, 2007; Bandiera et al, 2013). In the case of skulls and other such items where parts may be actually missing from wear or damage, 3-D technologies allow the modeling and creation of replacement parts or sections (Fantini et al, 2008; Zhang et al, 2007).

4.26. Education

Cross-curricular education in schools and colleges must overcome some challenges to be successfully implemented, including logistics and differences between various approaches traditionally used to teach subjects. The most common scenario where cross-curricular or “systems” thinking and practice are used is the development of design projects; students are typically given a particular mission statement or design brief and are expected to think and reason a solution to the problem, where they must make choices and decisions regarding the design. This is in heavy contrast with the way that subjects such as mathematics and science are taught, where the focus is on in-depth teaching of discrete concepts (DFE, 2013).

The promotion of “systems” thinking in students requires the making of decisions and the communication and the testing of those choices to establish their correctness; the utilization of 3-D printers will serve as an important and useful tool for this, as it will promote understanding, reasoning, and visualization of the learned concepts. The

Figure 4.26.1: Students Using 3-D Printer in School
www.3d-printers.com.au

application of AM technologies in education is useful at all levels, from elementary school through college. School projects can be made more useful and relevant to real-world applications by the use of 3-D printers, as the students gain critical thinking skills by being able to see and touch the results of their decisions and design choices. The difficulty of the assigned projects can easily be tailored to the age, interest and abilities of individual students, promoting creativity and offering more flexibility for school projects than was previously possible (DFE, 2013; Murray, 2013; Dickens et al, 2012; EduTech, 2014; Educause, 2012; Fidan, 2011). ***Figure 4.26.1*** shows students using a basic 3-D printer for a school project. A very complex and impressive student project (done at the University of Virginia) that was completely fabricated using a 3-D printer can be seen in ***Figure 4.26.2***.

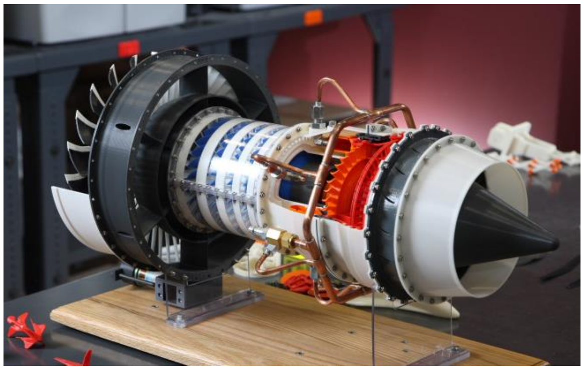

Figure 4.26.2: Student 3-D Printing Project
www.wired.com

There has been a movement in recent years to integrate 3-D technologies into classrooms and school labs (NMC, 2014). There are a number of possible subjects where it could be used, in addition to interdisciplinary work, as mentioned above; some of these are robotics, electronics, architecture, history, geology, geometry, and mathematics (Educause, 2012; Gonzales-Gomez et al, 2012; Choi & Saeedifard, 2012; Fidan, 2011). There are many stories of successful integration of 3-D technologies into public schools such as the Edina Public Schools of Minnesota (Edina, 2013), high schools such as Chico High in California (Chico, 2013), art schools such as Berea College in Kentucky (Berea, 2013), and engineering universities such as Cornell University in New York (Cornell, 2013).

4.27. Geographic Models and 3-D Maps

The mapping of terrain has traditionally been an important task, not only for record-keeping and perspective-gaining but also for travel planning, architecture, and military operations. With the development of computer technology, maps have gone from a paper-and-pen craft to one where accurate digital representations in three dimensions are common. There are many classical types of maps to represent relief and terrain lines, but these require skill and artistic ability to produce and interpret. Computer modeling relieves much of this burden, but it is still less intuitive and convenient than a physical 3-D contour map, such as the type used for hobby war gaming (***Figure 4.27.1***), which are expensive and general made by hand (Wang et al, 2014; Jenny et al, 2010; Haberling et al, 2008; Wargaming).

Figure 4.27.1: Hobby Models
www.joesoldiers.com

AM offers the capability to quickly and easily create these 3-D terrain maps directly from a CAD model or geographic information system (Lutolf & Fior, 2013; Rase, 2012; Groenendyk, 2013). Some of the numerous applications of these printed maps include urban planning and architecture

(Ghawana & Zlatanova, 2013; Sora, 2013), military planning (Mitra-Thakur, 2014), and maps of historical events for education (White, 2011). ***Figure 4.27.2*** gives some examples of 3-D printed maps.

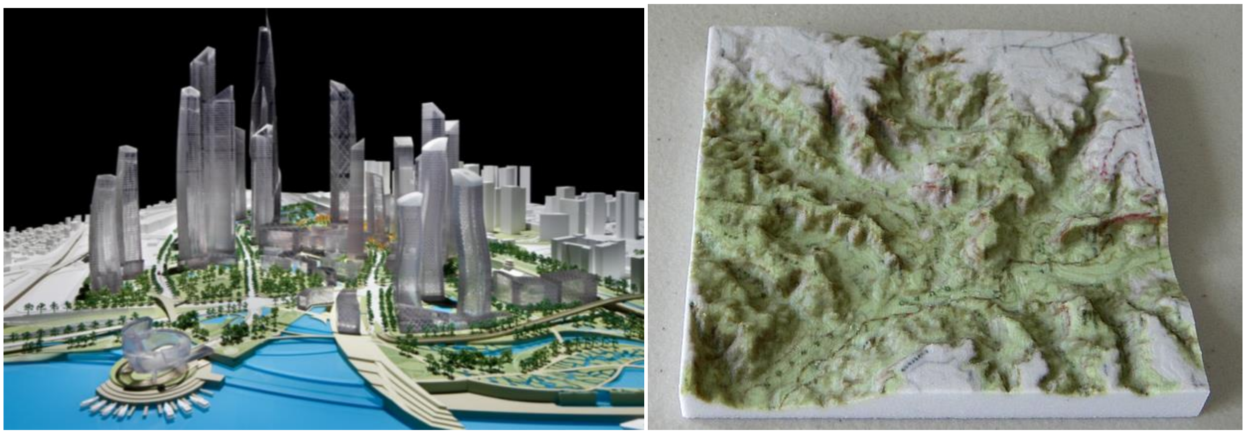

Figure 4.27.2: 3-D Printed 3-D Maps
www.creatz3d.com, 3dprinterlog.blogspot.com

4.28. Product and Material Tracking Technology

The facility of AM technologies to physically imbed electrical systems into material during fabrication is one of the major reasons to use the technology to produce integrated devices. There are many design advantages that come along with this, including the ability to directly embed RFID chips into parts and material (Gausemeier, 2011). There are several additive processes where this is possible, including ultrasonic consolidation (Siggard et al, 2006), laser melting (Fraunhofer, 2010), stereolithography, FDM (Deffenbaugh et al, 2013), and material jetting (Subramanian, 2010). Using additive technologies, RFID chips can be embedded in even the most complex parts, as seen in ***Figure 4.28.1*** (Fraunhofer, 2010). Research has shown that embedded RFID in additively manufactured parts work just as well as those embedded by other methods (Deffenbaugh et al, 2013).

Figure 4.28.1: RFID Chip Embedded Into AM Part www.ineffableisland.com

The full embedding of RFID chips into materials and parts offers many benefits. When the tag is embedded, it cannot be removed or tampered with without destroying the part itself; this helps to protect the chip from negative environmental influences, to assure that the parts are genuine, to deter theft and forgery, to correctly identify the appropriate parts for a give application, and aids in the tracking of stock in a storage facility. All of these abilities result in saved resources and prevented costs for users (Deffenbaugh et al, 2013; Subramanian, 2006; Sehrt & Witt, 2012; Fraunhofer, 2010; Isanaka & Liou, 2012).

4.29. Art and Sculpture

One of the earliest, most powerful, and still relevant applications for AM technologies is the creation of special art and sculpture pieces. The design freedom of the technology, as well as the ability to print in multiple materials, multiple colors, in a huge variety of materials, and its precision and accuracy, make it a perfect tool for artists to explore the possibilities of art and design. Art doesn't have the same "profit potential" as scientific applications of the technology; art is culture and an expression of humanity, which is priceless. However, the development of the additive technologies to benefit science (and to generate money, of course) benefits the arts as well, by refining the tools and methods and by bringing down the price of utilizing the technology. In turn, the utilization of technology in service of the arts benefits the sciences as well, by opening doors to new applications, by encouraging out-of-the-box thinking, and by offering new perspectives on design and form. However, not everyone is happy about computer-aided art; some artists see it as a profanation of their craft, but this attitude is beginning to change as more work is done on the technology and the great benefits begin to show themselves (Rees, 1999; Walters & Thirkell, 2007; Greer, 2013).

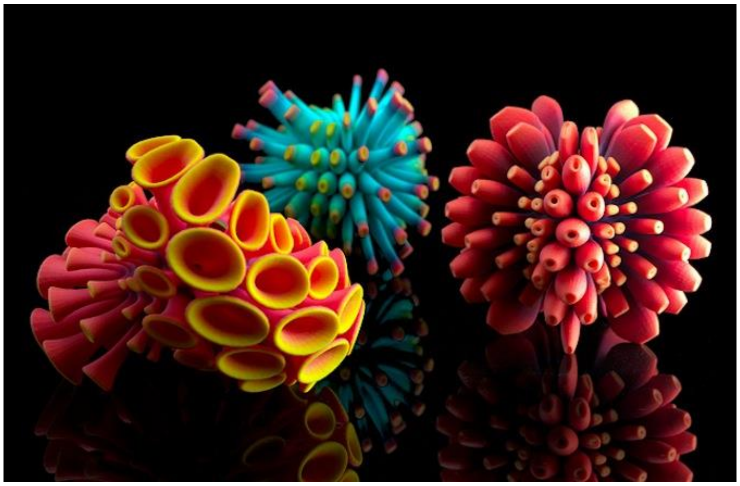

Figure 4.29.1: Free-form 3-D Printed Art
www.shapeways.com

AM technologies are already in common use to create artwork. The use of it is well-developed for the more "traditional" art forms, such as free-form and abstract art (***Figure 4.29.1***) (Oxman, 2010 & 2012; Chavez, 2014), ceramic arts such as photo-ceramic tiles and busts (Hoskins et al, 2009), bas-reliefs (Carfagni & Puggelli, 2014) and complex 3-D sculptures (***Figure 4.29.2***) (Gebhardt, 2012, pg. 83-85; Katz, 2014; Bathsheba, 2006; Greer, 2013; Hills, 2013). It is also being widely utilized for more unusual applications, including custom music boxes, crayon sculptures (3-D realization of a

Figure 4.29.2: Complex AM Sculpture
designspiration.net

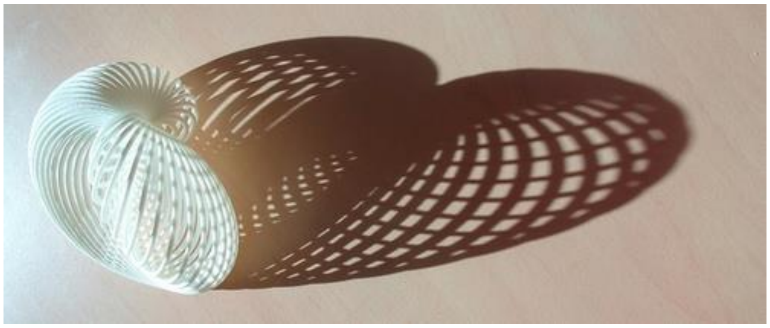

Figure 4.29.3: 3-D Printed Shadow Art
shapeways.tumblr.com

child's drawing), artwork with moving parts (Try it, 2013), shadow art (***Figure 4.29.3***) (Mitra & Pauly, 2009), sound-form sculptures (Walters & Davies, 2010), and sculptures of mathematical models (***Figure 4.29.4***) (Segerman, 2011).

In addition to assisting or facilitating the actual production of artwork, AM technology offers a number of benefits to the artists that are not directly related to current projects. The design freedom and customizable properties offers the possibility of exploring some old and possibly lost artistic techniques; for example, the self-glazing phenomenon seen during laser sintering and melting of ceramics is similar to that of an ancient Egyptian technology (Huson, 2013). 3-D scanners and printers can aid an artist by providing cheap and good copies of previous pieces to use as references during the work (Gebhardt, 2012, pg. 83), as well as supplying cheap and customized widgets to aid in the creation of multi-piece artworks (Molitch-Hou, 2014). The technology is so automated and simple to operate that is can give a new life to the work of handicapped artists, allowing them to make a living more easily and to be more independent (Spurling, 2013).

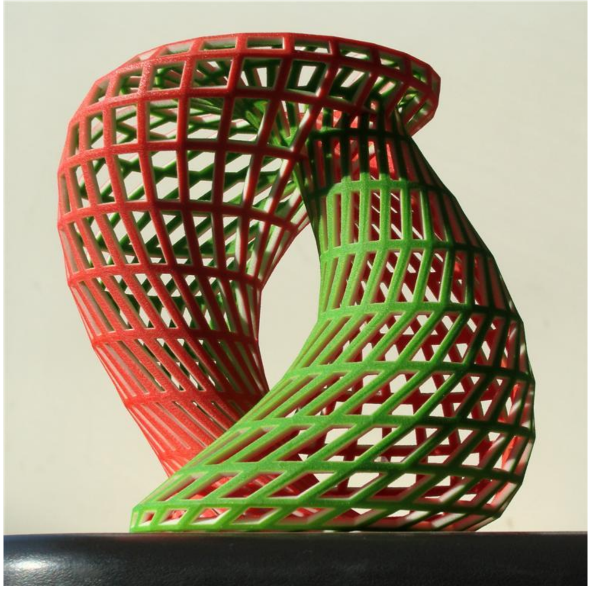

Figure 4.29.4: Mathematical Sculpture
www.cs.berkeley.edu

4.30. Mathematical Modeling

Visualization is a very useful and important tool in the communication of mathematics; models and drawings helped to explore and express ideas even before formal mathematical language has been developed. Mathematical visualization tools are especially useful in the study of geometry and for communicating proofs and intuitive conclusions. Physical models of mathematical concepts are very useful in education and can provide new insight to the students about the nature of mathematics (Knill & Slavkovsky, 2013a & 2013b). As mentioned briefly in *Section*

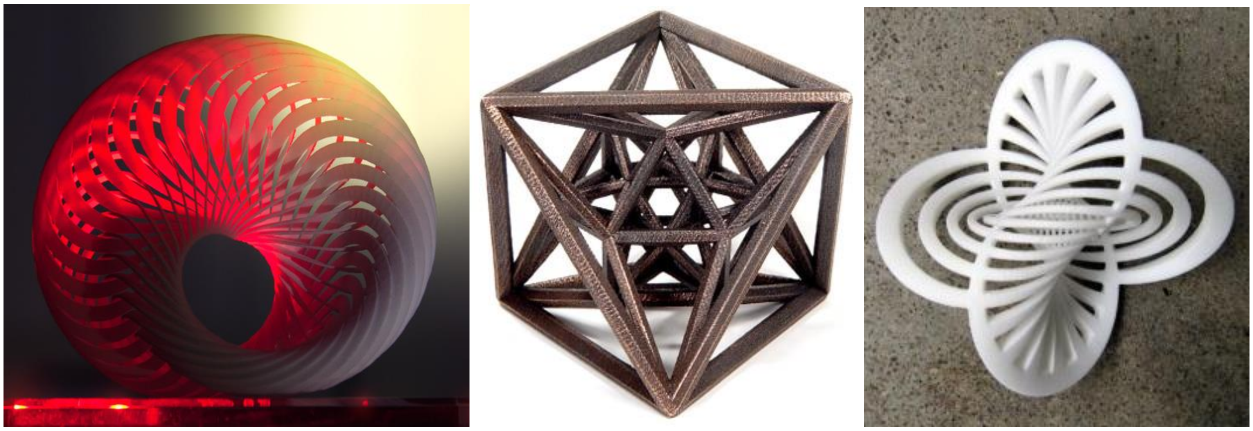

Figure 4.30.1: 3-D Printed Math Sculptures
www.shapeways.com, www.bathsheba.com, www.3ders.org

4.29 Art and Sculpture, the physical realization of math models is an interesting and useful application of AM. The huge amount of geometric freedom, the accuracy, low setup cost, and short lead time offered by the technology facilitate the quick and cheap production of these math models (Segerman, 2011 & 2012). ***Figure 4.30.1*** gives some examples of 3-D printed mathematical sculptures.

Chapter 5: Limitations and Challenges of AM Technology

5.1. Introduction

Additive manufacturing offers a huge range of benefits and has a plethora of applications, but also faces some very real boundaries. First, the technology itself has limitations, which vary from process to process. Next, there is a lack of knowledge about the long-term performance of the technology and about what kind of material and design properties can be gleaned from it. Process control is a real issue with this technology, but the establishment of industry standards can do a lot to mitigate this. Finally, there are issues with the computerized aspect of AM, both with the software and the users.

5.2. Technology Challenges

As with any technology, there are specific limitations to the abilities of additive manufacturing technologies. Things such as fundamental physical limits, materials characterization and development, process control and understanding, machine qualification and flexibility, and design challenges limit the usefulness and applicability of additive technologies. The fundamental limits that are inherent in any additive manufacturing process include the requirement of special materials (powders, resins, and so forth), the layered fabrication (which can limit the strength and durability of parts in certain orientations), and the slow fabrication speeds (Campbell et al, 2011; Brajlih et al, 2010).

5.3. Materials Challenges

One of the most challenging tasks yet to be done is the determination, cataloging, and publication of material properties and characteristics produced by the various processes. This is very important for the successful use of the technology in industry; in fact, it must be done before additive manufacturing can ever completely transition to a practical manufacturing establishment, as competent designers will not make use of a material whose properties they do not understand fully. Since the additive processes behave so differently from traditional ones, it is impossible to interpolate the properties from established technology, even when using the same materials. As the list of additive manufacturing processes and available materials grows, it will be become more and more difficult and expensive to glean and compile the material properties. This is a disadvantage for the development of new materials for additive processes, as it is difficult to design and develop new materials without fully understanding the limitations and capabilities of the old ones (Scott et al, 2012; Campbell et al, 2011; Dimitrov et al, 2006; Mahamood et al, 2014).

5.4. Process Control and Standards Challenges

While not as major of a concern as it was in the early days of the technology, process control is another potential headache when employing additive manufacturing. One of the major criticisms of additive manufacturing technology is the less-than-perfect consistency, tolerance control, repeatability, and uniformity across the machines. These all can be traced back to a lack of sufficient in-process monitoring, lack of understanding and experience by the operators, and lack of standards to govern machine qualification. If defects could be detected early through the use of sensors and cameras, time and resources could be saved, thereby reducing the cost of additive manufacturing and helping to establish a reputation of reliability. This careful monitoring would also be useful in the production of models to predict process behavior and adjust, as needed, the process to give the best results (Scott et al, 2012; Bourell et al, 2009; El-Katatny et al, 2010; Mahamood et al, 2014; Frazier, 2010; Berman, 2012). The issuing of industry standards on the design and calibration of machines in another issue that needs to be addressed. Currently it is possible to fine-tune a particular machine to give excellent results, but another (supposedly identical) machine may not give identical finish, properties, or repeatability, even with the same fine-tuning (Scott et al, 2012; Bourell et al, 2009; Brajlih et al, 2010).

5.5. Software Challenges

As mentioned above, the lack of reliable and useful material property data from additive manufacturing processes is a major impediment to the universal acceptance of additive manufacturing as a valid manufacturing process. Another is the challenges posed by the most basic need of additive manufacturing: the use of modeling and design software. This software has been getting less expensive and more user-friendly in recent years, but they are still issues with having to use several programs to design, optimize, and slice the parts before printing. This required more skill and experience on the part of the users, which put limits on its ability to be integrated into a manufacturing environment. Work has been done to integrate design, material properties design, and geometry optimization into a single software package, but the development has a long way to go (Scott et al, 2012; Frazier, 2010; Campbell et al, 2011; Dimitrov et al, 2006; Gibson et al, 2010, pg. 351-354).

Chapter 6: Sustainability, Environmental Concerns, and Industrial Hazards

6.1. Introduction

Sustainable manufacturing is a hot topic these days. Manufacturing in general has always been associated with unpleasant environmental side-effects, since the purpose of manufacturing is to transform natural resources into useful outputs. Over the past few decades, the environmental impact of industrial activity has become an important topic of discussion in society. A number of important factors play a role in defining the requirements of next-generation production systems, including a responsibility for environmental damage done by said system and from any industrial hazards that the technologies create. This encourages efficiency and technology development, while discouraging waste and pollution (Despeisse et al, 2012; Dias Pimenta et al, 2012). The sustainability and industrial safety of additive manufacturing technologies is an important topic of discussion, as this has the potential to become a next-generation manufacturing system (Drizo & Pegna, 2006; Le Bourhis et al, 2013).

6.2. Sustainability and Environmental Impacts

By its very nature, additive manufacturing eliminates costly and polluting supply chain activities, reduces waste by minimizing the use of material, and facilitates the repair of resource-intensive items like tooling and dies (Morrow et al, 2007). However, there has been little research done on the actual environmental impacts of emissions, energy use, and resource consumption of the additive manufacturing processes. Some work has been done that focused on resource flow and system modeling (Le Bourhis et al, 2013), energy use (Baumers et al, 2011 & 2012), supply chain management (Morrow et al, 2007).

There is no existing environmental legislation, emissions standard, or OSHA regulations for 3-D printers, but it is important to go forward with the development of the technology as if there were. There are three major benefits to this: (1) it will give responsible direction to the decisions made, (2) it will help facilitate the acceptance of the technology to the public and industry, and (3) it will increase the efficiency and safety of the processes, preventing lawsuits and industrial problems (Le Bourhis et al, 2013; Morrow et al, 2007; Drizo & Pegna, 2006).

6.3. Industrial Hazards

Almost no research has been done on the health hazards and industrial risks posed by additive manufacturing processes. It is logical to conclude that there must be some health hazards, as additive processes often involve melting of plastic, metal, or ceramic powders or the extrusion of plastic materials (Drizo & Pegna, 2006). Ultrafine particle emissions from small desktop printers have been studied very recently and the results are not at all encouraging; it was suggested that the emissions from an open-frame desktop extrusion printer in a poorly-ventilated environment might be as bad for health as second-hand cigarette smoke (Stephens et al, 2013). Obviously much more research in this area is needed soon.

Chapter 7: Legal and Ethical Concerns of Open-Source Manufacturing

A very real concern with additive manufacturing technologies, especially when they become mainstream and widely used by the public, is the potential for abuse and illegal activity. Direct manufacturing is a very powerful technology, one that puts the uncontrollable ability to manufacture almost anything into the hands of anyone with enough skill to use a no-cost CAD program and enough money to buy the hardware and materials. Often laws and regulations are criticized as restricting the free use and development of technology, but the story is usually more complex than it seems on the surface. Abuse and illegal exploitation could come in the form of pirating, patent infringement, illegal weapon production, and the facilitation of terrorism, among other things.

The pirating of art, proprietary designs, and copyrighted works via CAD file sharing is a very real concern, as these could be very easily printed out and sold, causing the artist or owner to lose revenue and possibly reputation (if the copies are shoddy and sold as genuine merchandise) (Finocchiaro, 2013; Doherty, 2012). The patent laws in the United States are not very clear about the legality of the reverse engineering, repair, or reconstruction of patented items that were actually purchased, so common sense should be used. However, if an item comes with a license agreement (such as a piece of industrial equipment), even the production of small replacement parts for such a system may constitute a violation of the law, depending upon the terms of the agreement (Wilbanks, 2013; Doherty, 2012). Typically, there are physical and financial impediments to violating patents, but the ability to quickly and easily 3-D print things complicates this (Desai & Magliocca, 2014). The infringement is clear and certainly unlawful when the user of the 3-D printer begins to sell, or benefit from the sale of, patented and copyrighted items that were produced using the open-source manufacturing technology (Doherty, 2012). However, there certainly are two sides of this argument and there are calls to modify the laws to allow the further (free and legal) development of open-source production for the benefit of humanity (Hornick & Roland, 2013).

3-D printing of firearms is a major point of contention for many people, whether they are dinky disposable plastic guns created for media attention (Gorman, 2013; Defense Distributed) or actual 1911's made out of metal (McGowan, 2014). While it is generally not considered illegal to create standard weapons (subject to ATF regulations and local laws and regulations, of course) in the United States, the online sharing of the CAD files and the widespread use of printers in many countries could create some major problems. In places where firearms, or at least untraceable ones, are illegal to produce, the ability of printers to create such items facilitates the violation of the law, which is certainly a major abuse of the technology (Johnson, 2013; D'Anna, 2013). Very unfortunately, the potential also exists for the technology to be exploited by terrorist organizations and cartels for the purpose of creating and disguising weapons without being dependent on developed countries for technology. This has massive national security and diplomatic implications and a solution needs to be found immediately (Campbell et al, 2011; McNulty, 2012).

Chapter 8: The Economics of Additive Manufacturing

8.1. Introduction

Additive manufacturing technologies show future promise for the defense, energy, aerospace, medical, commercial, and many other economic sectors. The ability to create things directly from the raw materials without the need of special tooling makes it a good alternative to traditional formative and subtractive manufacturing technologies. The field is rapidly growing; it is expected that the sale of additive manufacturing machines, materials, and service will constitute a $3.7 billion industry by the end of next year and $6.5 billion by 2019. The impact of using the technology on the US manufacturing sector is yet to be seen, as the technology has not been integrated yet (Baumers et al, 2012; USDC, 2014).

8.2. Technology Benefits

There are many benefits of using additive manufacturing, one of which is that design complexity does not affect the price for producing an item, as it does for subtractive and formative manufacturing processes. While the technology has many interesting capabilities, its long-term success is likely dependent on taking advantage of this. Customer demands and expectations can be hard to measure and change quickly; however, the speed and design freedom of additive manufacturing can help to mitigate the negative effects of this, as design changes and modifications are very simple. The new and exciting possibilities offered by additive manufacturing, to some extent, requires a new approach to the design and engineering of products; however, changing established practices can be difficult and will certainly be met with resistance. Additive technologies also require more input from the customers (since the products are customized; there is not a set list of feasible configurations for the customer to choose from) than more traditional methods and this can pose a challenge for certain manufacturers (NIST, 2013; White & Lynskey, 2013).

For both small-scale production and for mass production, additive manufacturing offers cost savings and opens up new alternatives for make-or-buy analyses (Ruffo et al, 2007). Since additive manufacturing is layer-based, there is a huge amount of design freedom; this offers a practical reason to redesign parts into the most efficient and cost-effective configurations and to simplify assembly configurations, as the manufacturing restrictions are gone. This saves resources and time when producing customized products, reducing the economic incentive for manufacturers to offshore manufacturing in certain sectors (Atzeni et al, 2010; Atzeni & Salmi, 2012). While best suited for making small volumes of very specialized products, it is also useful for making dies and tooling for mass production. Traditional metal tooling is very costly and the ability to make it on-demand has the potential to dramatically reduce the cost of mass-producing consumer products (Pessard et al, 2008; Pereira et al, 2012).

8.3. Technology Costs

The costs of utilizing the technology are a very significant factor in the decision for a manufacturer to utilize additive manufacturing. The total cost of the technology is spread out over several areas, most notably the machine (assumed to include software), the materials, and the labor (which includes training). The machine can cost anywhere from 50-75% of the total, while materials can run 20-40% and labor 5-30% of the total. Machines can cost a few hundred dollars for a desktop hobby machine to over a million dollars for an industrial-sized metal printer. The price of the materials varies greatly, from $18 per kilo for FDM filament, $75-125 per kilo for powder for laser sintering to much higher for specialized materials (NIST, 2013, Berger, 2013; 3Ders, 2014; Hopkinson, 2006). ***Figure 8.1.1*** shows some commercially-available additive manufacturing systems; the machine on the top left is a laser sintering machine (3D Systems Proto3000), the one in the top center is a commercial fused deposition modeling machine (Stratasys Fortus 400mc), the one on the top right is a material jetting machine (Stratasys Objet500 Connex3), the one on the bottom left is a stereolithography machine (3D Systems iPro 8000), the one bottom center is a binder jetting machine (3D Systems VX 500), and the one on the bottom right is a hobby desktop printer (3D Systems CubeX). ***Figure 8.1.2*** shows samples of materials used in additive manufacturing; left is metal powder (titanium), center is plastic filament (ABS and PLA), and right is photo-resin (polyester).

Figure 8.1.1: Commercially-Available Additive Manufacturing Systems
proto3000.com, www.stratasys.com, www.3dsystems.com

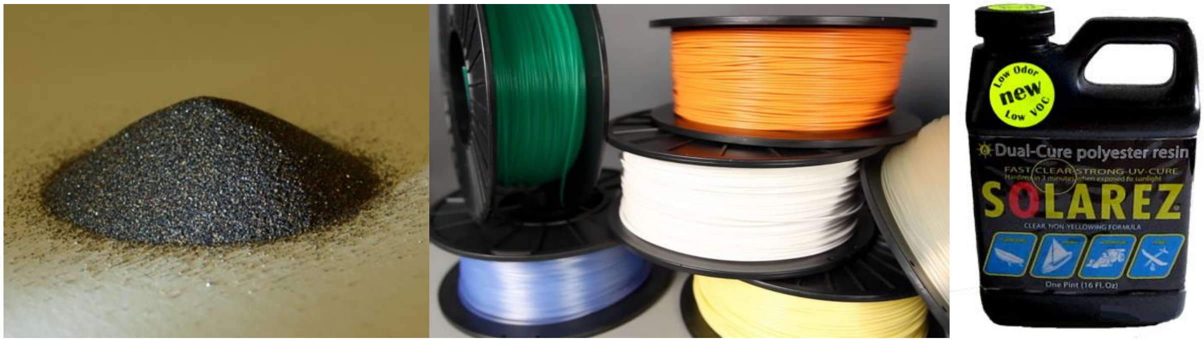

Figure 8.1.2: Additive Manufacturing Materials
inhabitat.com, prototype.asia, solarez.com

Chapter 9: Research To Be Done

9.1. Introduction

Additive manufacturing technologies are developing at a very rapid rate and are daily becoming more potent and capable. However, there is still a lot of work to be done, including identifying and extending new applications for the technology, improving existing processes and process control, identifying, understanding, and modeling material properties from the processes, developing industry standards to guide and govern the technology, identifying and correcting industrial and health hazards associated with the processes, exploring the legal and ethical questions surrounding the use of the technology, and developing design-for-manufacturability principles for additive manufacturing.

9.2. Future Applications

The range of possible future uses of additive manufacturing technology is virtually limitless, but some specific applications have been discussed as the future of the technology. Such sectors as building construction, electronics, scientific equipment, open-source technology, research in archaeology, paleontology, and pathology, solar panel manufacture, food production, medical technology, exotic structures, biotechnology, custom chemistry, light-weight parts, space exploration, energy and art can all benefit very much from the future use and development of additive manufacturing technologies; there are many, many others, as discussed in *Chapter 4 – Relevant Economic Sectors*, but this is a good sample. Some of these, such as medical technology and art, are already pretty well developed but need much more work. Others, such as solar panel manufacture and space exploration, are at the very beginning of their technological development. The future for the technology is wide-open and certainly not limited to a few niche industries and hobbies (Scott et al, 2012; Benwetsch, 2012; O'Reilly & Leal, 2010; Pearce, 2012; Zhang et al, 2012; Wegrzyn, 2012; Guo & Leu, 2013, Gibson et al, 2010, pg. 386-387; Cesaretti et al, 2014; Greer, 2013; Symes et al, 2012; Lu & Reynolds, 2008; 3D printing).

9.3. Process Improvements

There is a lot of work to do here, both to improve the current additive manufacturing processes and to develop new one for specific applications. Additive processes are notorious for being more difficult to control than subtractive or formative processes; this lack of good control is a major disadvantage for many users of the technology, as it leads to undesirable errors in tolerances, reduced the consistency and repeatability, and gets in the way of the uniformity of build between different machines. Work needs to be done on process monitoring and automatic control, in order to detect defects early in the process and to take data on the performance of each process to aid the development of future processes (Scott et al, 2012; Bourell et al, 2009; El-Katatny et al, 2010; Mahamood et al, 2014; Frazier, 2010; Berman, 2012). Good mathematical, selective, and predictive models of the additive processes will aid in the development of new processes and help improve the old ones and aid users in choosing the best process for a given application (Lan et al, 2005; Rao & Padmanabhan, 2007; Roberts et al, 2009; Singh & Prakash, 2010; Wiria et al, 2010).

9.4. Material Properties and Improvements

Being able to completely understand and predict material properties and characteristics is an important part of designing a product. Unfortunately, that is a very complex task for materials used in additive manufacturing. The determination, cataloging, and dissemination of information about these properties and characteristics is one of the most important prerequisites for the technology to be accepted and widely used as a legitimate manufacturing process. Additive processes behave very differently from traditional processes and produce very different properties, making it impossible to work out the properties from existing knowledge, even when using the same material. As more processes and variations of these processes appear in the technology, the ability to design materials becomes more and more important. At some point, additive manufacturing will either have to be recognized as a permanent part of manufacturing technology or disappear. It is becoming increasingly difficult and expensive to glean and compile the material properties as the technology gets more complex and wide-spread (Scott et al, 2012; Campbell et al, 2011; Dimitrov et al, 2006; Mahamood et al, 2014).

9.5. Standards Development

While additive manufacturing technology have been hailed as the next industrial revolution, the technology is currently operating and developing without many of the industry standards that characterize other advanced technologies. Issuing standards on terminology, materials, machines and processes is an important task that needs to be addressed in future research (Scott et al, 2012; Bourell et al, 2009; ASTM, 2012l; Maxey, 2013; Brajlih et al, 2010).

9.6. Industrial Hazards

There has been very, very little research done on the industrial hazards of additive manufacturing processes and machines. It would seem that processes involving melting and extruding plastic and melting metals and ceramics would also present health hazards. The small amount of work done on this suggests that there are serious health risks (Drizo & Pegna, 2006; Stephens et al, 2013), so it is surprising that more research has not been done.

9.7. Legality and Ethics

Once additive manufacturing technologies develop further, get less expensive, and become more widely used, there is always the risk that it may be abused and used for illegal activity. Additive manufacturing is (potentially) a very potent tool, one that puts almost unlimited ability to manufacture almost anything into the hands of anyone who can use a basic CAD program and has the money to buy a printer. Research needs to be done on ways to detect and prevent pirating, patent infringement, illegal weapons production, and other possible violations of the law when using additive manufacturing technologies (Finocchiaro, 2013; Doherty, 2012; Johnson, 2013; Campbell et al, 2011).

9.8. Design for Manufacturability

Design for manufacturability (DFM) is defined as the practice of making design decisions that reduce (or eliminate) manufacturing and assembly problems and costs. Essentially, DFM requires the designer to consider the manufacturing and assembly constraints involved in making the product in order to prevent the product from violating these limits; this in turn is to avoid problems in manufacturing and assembly and to minimize costs. While simple in principle, using this methodology can be very time-consuming and complicated to apply; an advanced knowledge of manufacturing and assembly processes, material properties, design procedures, and supplier capabilities is needed. DFM has become a science all its own, with a standard set of methods, tools, and practices (Gibson et al, 2010, pg. 283-285).

Additive manufacturing (AM) offers a great chance to apply DFM principles in a new way in order to maximize the benefits, as well as minimize the drawbacks, of the technology. AM offers the ability to realize extremely complex geometries without requiring any higher cost in resources or time over simple geometries, allowing both the optimization of the product without the traditional manufacturing constraints (Ponche et al, 2012; Gibson et al, 2010, pg. 283-285; Vayre et al, 2012). The idea has been put forward to create a design feature database to aid with the application of DFM to AM technologies, in order to share discoveries and speed the development of design-for-additive-manufacturing (DFAM) (Bin Maidin et al, 2012; Adam & Zimmer, 2014).

Chapter 10: Summary and Conclusions

The mission of this project was to answer the question "what exactly *is* additive manufacturing?" In order to accomplish this, a detailed survey of the technology, its applications, its users, its problems and disadvantages, its economics, and its future potential was done. The current and past peer-reviewed, technical, conference, patent, and educational literature was reviewed, compiled and summarized into this paper. Specifically, this survey looked at the basic idea, history, mechanics, applications, current and potential users, limitations, sustainability, legal and ethical aspects, economics, and future potential of AM technologies. The general conclusion was that AM technologies are very powerful and potentially revolutionary tools, but still suffer from some roadblocks that need to be overcome before the AM will achieve permanent status as a legitimate manufacturing method.

There are a large number of AM processes available, including binder jetting, powder and wire deposition, material extrusion, powder fusion, lamination, and photopolymerization. Some special variations that were explored include ultrasonic consolidation, contour crafting, cold gas dynamic manufacturing, aerosol jet printing, bioplotting, friction surfacing, and ice prototyping. The machines and materials for each of the processes were also discussed. It was concluded that most individual AM processes have a fixed set of application sectors in which they are best suited, but, given the wide range of special variations of the basic processes, the fundamental processes are very flexible and easily customizable if needed to a given application.

AM technologies have many possible applications, but these can be boiled down to three essential ones: rapid prototyping, rapid manufacturing, and rapid tooling. In addition to these basic applications, there are several special cases where AM technologies are commonly applied; these are secondary additive manufacturing, multiple-material manufacturing, functionally-graded material manufacturing, and hybrid layer manufacturing. Secondary AM and hybrid manufacturing are schemes to integrate AM technologies into existing manufacturing processes, while the other two are methods of generating special or heterogeneous properties into materials. The ability to do rapid prototyping, rapid manufacturing, and rapid tooling is a huge gain from using the technology. However, it is reasonable to conclude that AM technology is not limited to being successful only for the basic three applications, as evidenced by the other practical applications that have been found.

The list of possible users of AM technology is massive; this paper only looked as a sampling of them in order to gain an understanding of how widely used the technology is. The large number of applicable economic sectors, as well as the huge variety of these sectors, suggest that AM is seen by many people (as opposed to prototypers and a few niche industries) as a practical current and future technology. Therefore, it can be concluded that AM technologies have developed far enough so that they are beginning to be trusted by the public and industry leaders and are starting to be accepted as a normal and common tool for fabricating solid objects.

Unfortunately, AM has its share of problems and disadvantages. The processes themselves have limitations, there is a lack of knowledge about the long-term operation of the technology and about what kind of material and design properties it will produce, there are issues with process control, and issues with software and user integration. Another area of concern is sustainability and safety; additive manufacturing is more “green” than traditional manufacturing because it eliminates costly and polluting supply chain, reduces waste by minimizing the use of material, and facilitates the repair of resource-intensive items like tooling and dies so these do not have to be replaced as often. However, the technology is very complex and there are other ways that it can be an issue, such as in energy use and industrial safety. There has been some work done to develop models of resource use, energy use, safety, and supply chain management for AM processes. While these problems and disadvantages may seem to discourage potential users away from the technology, these problems are being researched daily. AM, like every technology, must go through a period of development and troubleshooting. It was concluded that these hiccoughs in the technology are a normal part of the development process and will not present an overwhelming hurdle for the use of AM in the future.

The two final aspects that were discussed in this paper are the legal and ethical issues and the economics of AM. Any unregulated and uncontrolled technology has the potential to be abused, whether it is to create illegal objects or for pirating. It was concluded that AM technologies, while they can be abused, are no more dangerous or risky than many other advanced technologies. This is good, as the field is rapidly growing; it is expected that the sale of additive manufacturing machines, materials, and service will constitute a $3.7 billion industry by the end of next year and $6.5 billion by 2019.

In conclusion, AM technologies are developing at a very rapid rate and are daily becoming more capable and advanced. However, there is still a lot to be worked out before it can take off as a real technology, such finding new uses for the technology, working out the bugs in the processes, improving process control, identifying, understanding, and modeling material behavior, developing industry standards to govern the technology, correcting any industrial and health hazards associated with the processes, exploring the legal and ethical questions surrounding the use of the technology, and developing a feasible and clear design-for-manufacturability methodology for AM.

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