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Overview of current additive manufacturing technologies and selected applications

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ABSTRACT

Three-dimensional printing or rapid prototyping are processes by which components are fabricated directly from computer models by selectively curing, depositing or consolidating materials in successive layers. These technologies have traditionally been limited to the fabrication of models suitable for product visualization but, over the past decade, have quickly developed into a new paradigm called additive manufacturing. We are now beginning to see additive manufacturing used for the fabrication of a range of functional end use components. In this review, we briefly discuss the evolution of additive manufacturing from its roots in accelerating product development to its proliferation into a variety of fields. Here, we focus on some of the key technologies that are advancing additive manufacturing and present some state of the art applications.

Keywords: *additive manufacturing, rapid prototyping, 3D printing, solid freeform fabrication, direct digital manufacturing*

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Introduction

It remains to be seen what the long term implications of additive manufacturing will be. In many regards, it is a technology that is still in its infancy and it represents a very small segment of manufacturing overall. That small segment is growing quickly but the future is by no means certain. Scarcely a quarter century has passed since the first stereolithography systems for rapid prototyping appeared on the market. In that short time, additive manufacturing has not only become relatively common place in science, academia, and industry, but it has also evolved from a method to quickly produce visual models into a new manufacturing paradigm. In the past two decades, revenues associated with products and services show that additive manufacturing has grown into a multi-billion dollar industry[1].

Additive manufacturing has the potential to radically change the way in which many products are made and distributed. Throughout history, key innovations in manufacturing technology have had a profound impact on our society and our culture. An examination of the applications and technologies reviewed here suggests that additive manufacturing may become a truly disruptive technology. To understand just exactly how disruptive a technology additive manufacturing is, we must examine the historical context of traditional manufacturing.

Prior to the industrial revolution goods were typically produced by skilled artisans and were often tailored to satisfy a specific, individual demand. While this approach may have had many inherent advantages to the consumer (*i.e.* high quality, custom parts on demand) it is doubtful that system could have persisted under the growing demands of society. The invention of the first machine tools (that is tools capable of precisely controlling the relative motion between a tool and a work piece) along with advances in fixturing and metrology facilitated the manufacture of interchangeable parts which, in turn, supported the development of the mass production system. The model of mass production also has many clear advantages to both the producers and the consumers of products, including; high throughput, high quality and product consistency at a low unit cost. This, of course, comes at the cost of reduced product diversity.

In the last century, the means by which many goods are manufactured has been radically enhanced by computer controlled machinery and automation. However, in general, the basic methods and materials are quite similar to those used at the turn of the 19th century. Bulk materials must still be either cut, formed, or molded in order to fabricate value-added products. In fact, a large portion of the products that we consume or use at the present time are manufactured using processes like forming, injection molding, casting, extrusion, stamping, and machining. Each one of these processes requires some form of tooling (mold, die, flask, stamp, fixture, *etc.*). For instance, if we consider casting an exhaust manifold in steel we must first design and fabricate a sand or investment mold with the negative shape of the final part. A metal stamped part, as simple as a washer, requires a die and a large stamping press in order to be produced. A simple plastic cover for a smart phone requires an injection mold that may cost thousands of dollars and an injection molding machine that may costs hundreds of thousands to millions of dollars. The cost and time dedicated to the design and fabrication of tooling that supports mass production represents a significant percentage of the total cost of a product.

The natural result of high tooling costs is that within a given mass production system there is an inverse relationship between the quantity of a product that is produced and the variety of product designs available. It is necessary that we recognize that production tooling is not only expensive, but it also constrains the design of products based on innate limitations imposed by the various mass production processes. This is a widely studied area of manufacturing known as design for manufacture (DFM).

As a brief example, consider a plastic injection molded part. One of the key limitations is that the mold must provide for the easy removal of the part. This means that the part must have slightly outward sloping surfaces (called positive draft), as inward sloping surfaces would essentially lock the part to the mold like a dovetail making it impossible to remove. Further, the injection mold itself must be precisely machined, ground, and polished from a block of metal, and the processes that are used to do that, like milling with a cutting tool, also have similar limitations (*i.e.* the cutting tool must be able to access the feature that will be cut). Increasing the complexity of the part to better serve a given function can drive up the cost of the tooling required for producing it and, in many cases, the optimal design for a given purpose is impossible to produce using traditional mass production methods.

Additive manufacturing represents a fundamentally new method of part fabrication. It is the process of fabricating components directly from 3D computer models by selectively depositing, curing, or consolidating materials one layer upon the next. Each layer represents the cross-sectional geometry of the part at a given height. This is a stark contrast to traditional manufacturing processes like forming, casting, and machining because tooling is not required to produce a part. The freeform nature of additive manufacturing is therefore changing the way we look at traditional DFM constraints. In many cases the traditional constraints no longer apply. By building parts additively, in layers, components can be manufactured with extremely complex geometries, such as internal channels, undercut features, or engineered lattice structures with controlled and/or variable porosity. These are features that are extremely difficult or impossible to produce with traditional methods.

The implication of this is quite simple to recognize but at the same time has a profound result. Removing the need for tooling facilitates the economical production of small lot sizes of parts (as low as one) without sacrificing interchangeability, thereby reducing the lead time for production (because the tools do not need to be produced), allowing flexibility in the supply chain and the production location (parts can be made where and when they are demanded), and raising the possibility of transitioning from a system of mass production to one off mass customization[2]. It also means that design changes incur much less cost in production so products can potentially be customized to conform to the needs of the individual consumer. In many ways this concept goes far beyond the definition of most existing mass customization models in which mass produced components are fabricated and then assembled on demand to specific customer orders.

Background and origins

Rapid prototyping first emerged as a means to accelerate the time consuming and costly process of iterative product design, thereby reducing time to market, improving product quality, and ultimately reducing the costs. Traditionally, one of the difficulties with bringing an idea to the market was that the production of prototypes of new designs often required the same or similar expensive tooling to those used in mass production. These "traditionally made" prototypes would then be evaluated and tested. Any problems uncovered, either in function, fit, or from marketing studies would be corrected and a new prototype would be designed and fabricated. This process would repeat until the final product was ready for production, which could take anywhere from six months to several years. Naturally, this approach was very time consuming and expensive. By printing physical prototypes directly from three dimensional computer aided design (CAD) data, rapid prototyping offered designers the opportunity to quickly run through many design iterations and conduct market studies. This benefit has become even more vital today since product life cycles continue to decrease and companies must develop new products in order to remain competitive.

This was essentially the impetus for the development of the first rapid prototyping systems, called stereolithography apparatus (SLA), patented by Charles Hull in 1986 (Patent #US4575330) and marketed by 3D Systems. Stereolithography is based on the concept of photopolymerization by which monomers are linked into a polymer chain using photons. In stereolithography, a laser beam spot is numerically controlled by mirrors to trace the profile and raster the area of a cross section of a given geometry onto the surface of a photo-curable resin. The first layer is supported from below by a vertically actuated platform. The wavelength (UV), intensity, and exposure are carefully controlled to cure the resin. After the layer is completed, the build platform is lowered, the resin is allowed to settle (or spread across the surface) and the process repeats for the next cross section of the part geometry. Overhanging and down facing surfaces of parts must be supported from below by a network of structures that are generated as part of the build file. A very detailed description of the stereolithography process is provided by Jacobs[3].

One of the keys to unlocking the potential of layer based additive manufacturing was the development of the standard STL file format. STL (or stereolithography) is currently used by most additive processes and is available as a standard format on most CAD systems[4]. The STL format describes the external surface of the 3D CAD model with a series of triangular facets connected at the vertices. The STL data include the XYZ Cartesian coordinates of each vertex, as well as a vector normal to the triangle face (which indicates which side of the triangle represents both the inside and the outside of the part). The size and number of triangles can vary depending upon the accuracy of the process and the tolerances required. The STL part model is oriented in Cartesian space and software is used to slice the model parallel to the XY plane in discrete increments equal to the layer thickness. Because the vertices of each of the surface triangles are known, it is a relatively simple matter to calculate the coordinates of the intersection between the triangles and the slicing plane. These intersection points are connected to form the contour of each layer that is then used to control the machine (Figure 1A).

While approximating CAD surfaces with triangles is an effective and simple method for representing geometries and slicing models, it should be noted that it inherently builds geometric errors into the fabricated parts (Figure 1B). This can be partially offset by reducing the size (and increasing the number) of the facets, but only at the cost of increasing the data storage requirements. It is clear that additive processes can reduce or eliminate the need for traditional DFM constraints, however, they also introduce a new and quite different set of constraints on designers. For instance, each layer or slice of the part approximates a discrete representation of the cross sectional geometry. As one layer is stacked upon the next, a geometric stair-step error is introduced. This error is intrinsic to all additive processes (Figure 1C). Other geometric limitations often encountered in additive processes include minimum wall thickness and build orientation (properties are highly dependent upon build orientation). For many, if not most, applications limitations like these would normally not cause a

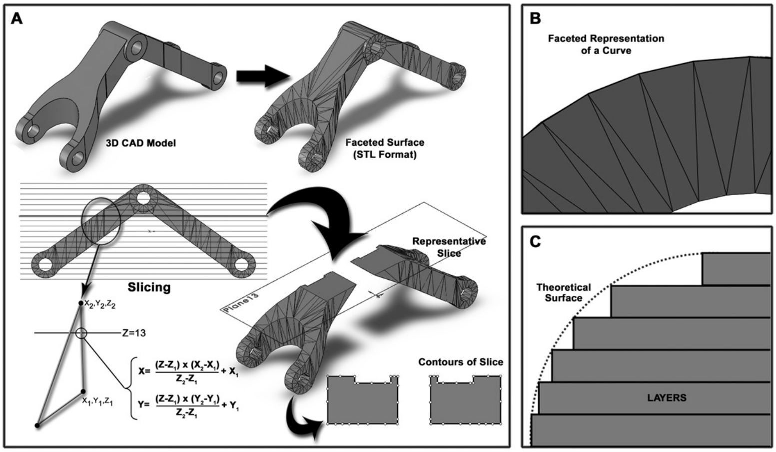


Figure 1 ***(A)*** *The process of converting a three-dimensional CAD geometry to a .STL surface model. The coordinates of the intersection points between the slicing plane and the legs of each facet are calculated and then connected to form the geometry of each slice contour.* ***(B)*** *The geometric error that results from approximating a curve with line segments.* ***(C)*** *The geometric error that results from approximating a three dimensional geometry with discrete layers.*

problem in particular for models intended for evaluation, visualization, or demonstration. To this point, the constraints associated with additive processes have not been studied to the same extent as with traditional manufacturing. A thorough accounting and standardization of these constraints will likely be a key factor in widespread adoption of additive manufacturing as a production tool. As products produced with additive manufacturing technologies are implemented in various industries and are incorporated into complex assemblies, tolerances to geometric errors such as these are likely to become more and more critical.

Additive manufacturing systems

Very soon after the development of the stereolithography technology many different types of rapid prototyping processes were developed and are still widely used today. As it would be impossible to include an adequate description of each, we are including several sources in the reference list that provide an in depth discussion of the many additive manufacturing processes[3-5]. While there are a wide variety of technologies, most of these operate on the same underlying principle that material is selectively cured, consolidated, or deposited layer upon layer. The following section provides a brief overview of some of the key processes.

One alternative approach, which can reduce processing times and the high cost of components typically associated with stereolithography (specifically lasers), is to use digital light projection technology (DLP). With DLP the silhouette of each layer is projected onto the surface of a resin that is cured by light either in the visible or the UV spectrum. These systems typically have the build platform inverted so that the finished parts are upside down; this has the added benefit of minimizing the amount of material required in the build tank at any given time.

Very soon after the development of stereolithography, the use of inkjet printing technology to deposit a binder onto a powder bed in a layer wise fashion was developed by a research group at MIT and marketed to numerous companies in the early 1990s[5]. Collectively, technologies that utilize print heads to deposit materials are now referred to as 3D printing technologies. This approach offered a relatively low cost solution for printing 3D models. One of the advantages is that these systems are capable of producing full color models which can accurately depict the appearance of a finalized product design and has even been used to demonstrate finite element analysis results. While inkjet printing systems have usually been used for product visualizations, models can be infiltrated with different materials such as epoxy or even room temperature vulcanizing rubbers to achieve a range of material properties. Inkjet printer models have also been used for the direct fabrication of ceramic shells for investment casting[6]. Other systems deposit a binder on metal powders; the resulting 3D model can be sintered and infiltrated with another metal (such as bronze) to produce metal parts. A detailed review of 3D printing technologies is provided in the references[7]. Similar inkjet printing technologies have also been used to deposit photosensitive resins which are then subsequently cured by a UV light source. One benefit of this method is the ability to print multiple materials or colors within a single layer. The same concept also facilitates the fabrication of products with functionally graded materials wherein the composition of a component can gradually vary from one material to another resulting in unique properties that cannot be achieved otherwise. One of the key barriers to the practical implementation of this is the absence of a generalized CAD format that can accommodate and translate functionally graded material data.

Another technology that was developed relatively early on is the deposition of thermoplastics by extrusion through a heated nozzle. This typically involves feeding a filament of thermoplastic, such as polycarbonate (PC) or acrylonitrile butadiene styrene (ABS), through an extrusion nozzle which is translated about a build platform using numerical control. The process has often been described as an automated glue gun. The extrusion speed, temperature, and nozzle travel rate are controlled to selectively deposit the material onto a build platform or previous layers, fusing one layer onto the next. While this technology often utilizes commercially relevant thermoplastics as a raw material, the nature of the deposition process results in parts with anisotropic properties. The technology was originally called fused deposition modeling (FDM®) which was marketed by Stratasys Inc. Recently many of the original patents on this technology have expired. Due in part to the relative simplicity and the availability of safe, cheap materials, these thermoplastic extrusion technologies are now relatively inexpensive. The price point has dropped low enough that these machines are accessible to the general public.

If additive manufacturing is going to become a commercially relevant production tool for fabricating functional components a wider variety of materials will be required. Laser sintering (LS) is one technology that offers the potential to address this need. Rather than using a laser to cure photosensitive resins, the laser energy is used to heat and consolidate layer upon layer of polymer powder. In theory, this suggests that any thermoplastic that can be rendered into a powder form of the appropriate size and morphology could be processed using LS. Typically the resulting parts are only sintered (partially melted and consolidated) but still strong enough to be used for many applications. One advantage of LS, like other powder based additive manufacturing systems, is that there is no need for support structures underneath down-facing or overhanging surfaces. The powder naturally serves this purpose and is easily removed after the part has been completed. While much of the recent work in this area has focused on the development and use of industrially relevant materials (including composites) the practical utilization of LS for the fabrication of polymer components is currently restricted to a relatively small number of materials. According to a recent study this limited use may be attributed to several factors beyond insufficient material properties including: the limited availability of polymers in powder form suitable for processing with LS, the lack of consistency between machines, lack of process control and repeatability, and the narrow process parameter window of many of the materials[8].

The importance of utilizing industrial materials for additive manufacturing is by no means limited to polymers. The recent development of direct metal technologies is indicative of the transition from rapid prototyping to additive manufacturing of functional components. The printing of metal parts has for many years been seen as the next frontier of additive manufacturing. The initial attempts to produce metal parts with additive processes were indirect, meaning that they were used to create tooling for metal forming processes rather than making the parts directly. For instance, resin and wax based components have been printed for the fabrication of investment casting shells and sand casting forms from which parts could be cast. The ability to completely eliminate the tool from the production equation and to fabricate parts directly from metals has generated significant interest in a wide variety of industries. As it turns out, in addition to the fabrication of parts using polymers, LS systems are also capable of processing metals. However, components made using LS are often porous, and require subsequent post sintering/heat treating in order to achieve acceptable material properties. A newer adaptation of the same technology called laser melting (LM) has the capability to fully melt rather than sinter the powder. This, however, requires a high power laser, but generally eliminates the need for secondary sintering. Although the surface finish and accuracy is considered very good, components naturally have high internal stresses caused by thermal gradients induced during processing and therefore require post build heat treatment[9]. One of the distinct advantages, like polymeric systems, is that in theory a wide variety of metal materials can be processed in this way.

Using a laser to melt metal powders is not the only metal additive manufacturing technology. Rather than controlling the position of a laser spot over the surface of a powder bed, a family of technologies called directed energy uses a focused energy beam (laser or electron beam) to melt metal powders or wire that is deposited by a nozzle. The substrate platform is typically mounted on a computer controlled stage to create a weld pool in which the deposited materials are simultaneously fed by a delivery system. The substrate is moved beneath the stationary beam to deposit a thin cross section, thereby creating the desired geometry for each layer. After deposition of each layer, the nozzle and beam assembly is incremented vertically and the process repeats; building a three dimensional component with each successive layer being supported by the previous ones. In the case of wire feed systems, there is an increased interest in applications involving microgravity environments. However, relatively low accuracy, internal stresses (from thermal processing), and high porosity are several of the main disadvantages of these systems. In addition, directed energy systems are not adept at producing overhanging features because of the difficulty in producing supporting structures. However,the nature of the process does facilitate the deposition of material in five or more axes (as opposed to just three). This makes directed energy technologies an interesting solution for the freeform repair of complex metal structures.

Another direct metal additive manufacturing technology uses ultrasonic energy to produce solid state bonding between successive layers of thin foils and this process is called ultrasonic consolidation. A computer controlled milling machine is then used between each layer to cut the cross sectional geometry of the part from each bonded layer. This technology represents a hybrid, additive-subtractive process. Primarily because the ultrasonic consolidation takes place at low temperatures, the resulting parts exhibit high accuracy without the internal stresses that are common with other direct metal additive manufacturing processes. A benefit associated with low temperature bonding of layers is the potential to embed sensors and electronics into components as they are being fabricated. The solid state bonding process also facilitates the layering of dissimilar metals and even ceramic based metal matrix composites[10].

A relatively new direct metal additive manufacturing technology is the electron beam melting (EB) process. Like LS and LM, EB is a powder based process. However, rather than using a laser beam to melt or sinter powder, a focused electron beam is used to selectively melt layers of powder. First, a tungsten filament is heated to over 3000º C which causes electrons to be emitted; then a potential difference between a cathode and an anode causes the electrons to accelerate. The electrons are focused and deflected using magnetic coils to form a narrow high energy beam that strikes the surface of the powder. When this happens, the kinetic energy transferred through friction creates the heat that is necessary to melt the metal powder. This makes EB a very energy efficient process when compared to laser light which is mostly reflected away from the melt pool during processing. The energy density within the electron beam can be as high as 106 kW cm^{-2}. The process is carried out inside of a vacuum chamber in order to prevent scattering of the electron beam caused by collisions with gas atoms. Further, the vacuum environment prevents oxidation of the hot metal materials and greatly reduces the risk for contaminations. The electron beam is also used to periodically scan the powder bed in order to maintain a high temperature inside the build chamber which greatly reduces internal stresses caused by thermal gradients. Parts fabricated using EB typically have a surface roughness that is comparable to cast parts due to the sintering of particles adjacent to the melt pool. Materials fabricated using EB can be fully dense and with properties closely matching the values found in cast and wrought materials with similar composition. The principal advantages of the EB process are the relatively low input energy required, the good mechanical properties of the finished components, the ability to fabricate in a vacuum (which is important for highly reactive metals such as titanium), and the ability to manufacture relatively large metal components without high internal stresses. The key limitations of the process include relatively high expense and relatively small build volumes. Another important point is that although the high energy density is capable of melting most materials the electrons must have a pathway to ground which usually limits EB to the processing of metallic powders.

The current state of additive manufacturing

The direct fabrication of parts using additive manufacturing has many distinct advantages that have been briefly touched on. There is currently a great deal of excitement directed towards the additive manufacturing of metal components for a variety of applications. This technology has the potential to facilitate the use of new materials and geometries that may not have been possible before. However,we must be mindful that parts produced using additive manufacturing will almost certainly require secondary post processing or machining operations just like any other near net shaped parts, especially if these parts are expected to be used in moving assemblies. The issues of achieving tight tolerances (of which surface finish is only one of many) will become paramount. This brings new challenges, such as efficiently and economically post processing freeform components with a batch size of as low as one.

Of the polymer processes that have been discussed, while some are currently suitable for additive manufacturing, most are still only useful for prototyping, visualization and demonstration. Parts made using photopolymers are typically brittle and exhibit poor mechanical properties. Furthermore, nearly all rapid prototyping processes result in parts with a relatively high degree of anisotropy. Generally speaking, the variety of materials that are readily available to designers and engineers wishing to utilize additive manufacturing is severely limited. Nevertheless there is currently a moderate variety of materials and significant progress being made in the development of new materials. Additive manufacturing is still most commonly used for modeling and prototyping, but as the technology progresses towards the manufacture of production quality parts a wider variety of materials capable of meeting commercial standards needs to be investigated.

We have discussed that one of the key advantages of additive manufacturing is that it may eliminate the need for the tooling and long lead times required to produce a part. This, in turn, facilitates the practical implementation of small batch size production. Taking this concept one step further, additive manufacturing opens the possibility of pushing the manufacturing stage downstream closer and closer to the consumer, allowing products, or families of products, to be produced to meet individual consumer requirements. The changes in traditional DFM constraints also hints at the possibility of the consumers themselves modifying or even designing products and then manufacturing them, perhaps in their own homes.

While to a large extent the interest focused on agile decentralized manufacturing is beginning to become apparent, current technological limitations indicate that not all products are presently well suited or practical for economic production using additive manufacturing. For instance, consider an injection molding machine that may be capable of producing hundreds of thousands of uniform, FDA approved, statistically controlled and certified petri dishes for cell culturing. In cases such as this it clearly will make more sense to rely on the traditional injection molding process at the present time. So the question becomes, under what circumstances does production using an additive manufacturing process make sense? From a purely economic standpoint, the tool-less production of the simple petri dish using additive methods might result in extraordinarily high unit costs. However, the elimination of traditional DFM constraints has a deceptively broad impact; it is not simply a matter of producing the same products that would have otherwise been made using traditional methods and materials. To truly capitalize on the freedom of design that additive manufacturing has to offer an entirely new thought process is required. Consider that same petri dish with a network of internal microfluidic channels designed for carrying out a specific set of complex experiments. The current state of additive manufacturing technology readily addresses the need to make unique and complex value added products in small quantities. The following section highlights a few specific examples and research efforts in which additive manufacturing has been used to this effect.

Applications of additive manufacturing for aerospace materials and components

In the aerospace industry, additive manufacturing has started to gain acceptance for several reasons. First, it has the potential to greatly reduce the so called buy to fly ratio (the mass of the material required to manufacture a part divided by the mass of the final part that flies on the airplane). For many aerospace parts processed using traditional methods, this ratio can be as high as 20:1. With near net shape parts fabricated with tool-less additive manufacturing, the buy-to-fly ratio approaches one. The efficient use of material is often a vital concern for many aerospace applications. High performance alloys used for aerospace applications (Ti-6Al-4V, Inconel 625, GRCop-84, *etc*.) are typically associated with high prices. The machining of chips from a billet is not efficient or economical for many of these materials. It is often the high cost of these materials that points to the need for near net shape manufacturing processes. The utilization of high performance, exotic materials can be greatly increased as direct metal additive manufacturing systems only consolidate the material that is required for the near net shape part, so that the raw material (powder metal in most cases) may then be recycled several times without adversely affecting the physical properties. One such alloy that has generated a great deal of interest is titanium aluminide (Ti-Al). Gamma phase TiAl (γ-TiAl) has many properties that are of particular interest to the aerospace industry for the fabrication of blades used in high speed gas turbine engines. For instance, at high temperatures γ-TiAl exhibits low density and retention of specific strength, modulus, creep and corrosion resistance. However, despite the desirable characteristics of γ-TiAl, one of the major barriers to its widespread use has been associated with difficulties in processing. Typical problems in processing include porosity, chemical inhomogeneities, and poor microstructure (the properties of γ-TiAl are highly microstructure dependent). For extrusion and forging, the manufacturing costs are extremely high, the internal microstructure is very difficult to control and most heterogeneities can be traced back to the source ingots used. Casting of γ-TiAl has not been able to produce satisfactory results either. The high reactivity of the material coupled with high porosity has resulted in scrap rates as high as 80%[11]. Direct metal additive manufacturing offers a cost-effective route for the production of complex shapes in γ-TiAl . By using pre-alloyed powders as a source material, the layer-wise process is capable of producing a much more homogenous composition[12]. Biamino *et al.* showed that the electron beam melting process could be used to successfully fabricate γ-TiAl components with an axial length of 300 mm (Figure 2A) with homogenous composition, fine grain structure and low porosity.[13] This clearly demonstrates a production scenario in which the benefits of additive manufacturing outweigh the costs, facilitating the manufacture of a product that was virtually impossible before.

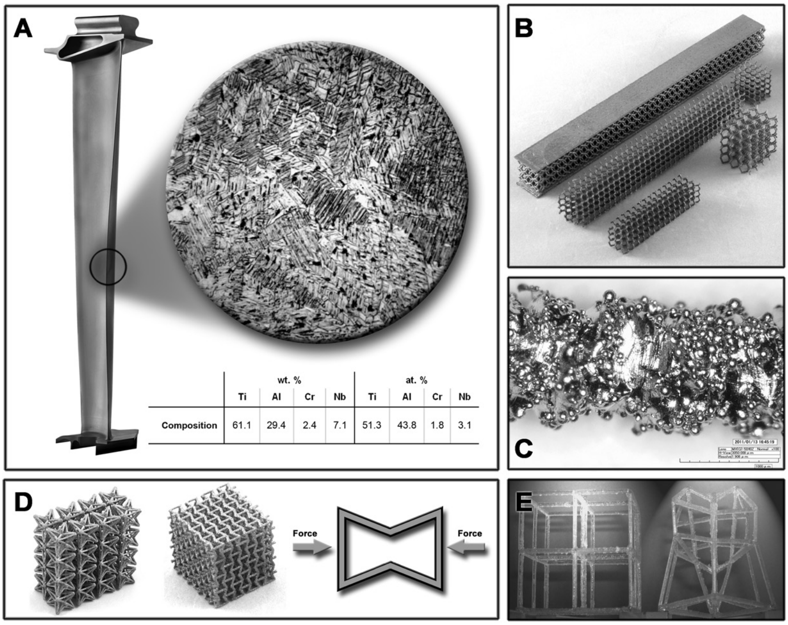
Additive manufacturing for structural optimization

Structural foams have been used for a wide variety of applications, from weight reduction and impact absorption to filters and heat exchangers. Traditionally these foams have been fabricated by generating gas bubbles in moulten metal or plastic (closed cell foams) or by vapour deposition of metal onto carbon scaffolds (open cell foams). These methods result in what are known as stochastic structures, that have random variations in the size, shape and distribution of cells[14]. For a long time, theoretical non-stochastic structures, with repeating unit cell geometries or precisely determined characteristics were the subject of mathematical interest but the lack of production methods to fabricate such structures presented a significant barrier to their use. Additive manufacturing technologies facilitate the production of non-stochastic structures in a wide variety of materials with geometries that can be optimized for a given set of constraints (Figure 2B). Research in this area has also uncovered some interesting limitations of the additive processes with respect to non-stochastic foams such as identifying minimum strut angles that can feasibly be built or reconciling the differences between the idealized computer model (CAD, finite element *etc*.) and the true manufactured geometry of individual lattice struts (Figure 2C)[15]. Additive fabrication of non-stochastic lattice structures also introduces the possibility of fabricating components with unique properties such as auxetic constructs, that is, a component that exhibits a negative Poisson's ratio. Poisson's ratio describes the ratio of the transverse strain (perpendicular to the applied load), to the axial strain (in the direction of the applied load). In modest terms, most materials get thinner in the middle when they are stretched and, fatter in the middle when they are compressed because of the conservation of volume. Auxetic structures exhibit the opposite behavior which has many interesting applications, from energy absorbing structures and blast attenuation, to the development of components that exhibit very low thermal expansion at high temperatures (Figure 2D).

The design of structural aerospace components often involves making trade-offs between conflicting objectives. Many optimization criteria can be used but weight reduction while maintaining a specified stiffness, strength or displacement is a very common goal. Reduced weight in one or more components can significantly improve the fuel carrying capacity, range, and manoeuvrability of the structure. The challenge is to reduce weight without compromising strength – particularly at higher temperatures.

Without traditional DFM design constraints, there has been a renewed interest towards utilizing shape and topology optimization. When complex organic structures such as wood or bone are examined it is striking how structural material is only used where it is needed (*i.e.* where there is a stressor). The same concept can be extended to engineering structures, however, many of these freeform organic structures cannot be made using traditional manufacturing methods. A layered approach to manufacturing not only takes advantage of advances in structural optimization that have been hitherto unrealized, but also incorporates structural optimization into an entirely new class of products.

In topology optimization, the material is represented by voxels (three-dimensional pixels) constrained by some predefined geometric boundaries. Loading and support conditions are defined along with objectives like minimizing weight. The output is generated by iteratively adding or removing voxels of material until all of the constraints are satisfied. Similarly, the finite element method has been used to optimize the loading performance of non-stochastic structures based on various loading conditions (Figure 2E)[16] .



	wt. %				at. %			
	Ti	Al	Cr	Nb	Ti	Al	Cr	Nb
Composition	61.1	29.4	2.4	7.1	51.3	43.8	1.8	3.1

Figure 2 (A) *Titanium aluminide turbine blade fabricated using EB (photo courtesy of Arcam AB, Sweden), the microstructure and composition are also shown.* ***(B)*** *Examples of titanium alloy (Ti6Al4V) non-stochastic lattice structures fabricated using EB.* ***(C)*** *The geometry of a single strut from a Ti6Al4V lattice fabricated using EB, the surface roughness and variations in the geometry pose new challenges for modeling.* ***(D)*** *Examples of Ti6Al4V structures made using EB that exhibit a negative Poisson's ratio and, an illustration showing the face of one of the unit cells.* ***(E)*** *An example of structural optimization, the seed geometry (left) and the optimized geometry based on specific loads and constraints (right). The samples in B–E were fabricated at NC State University.*

Optimized thermal management

There has been growing interest in the use of additive manufacturing for the fabrication of structures that have been designed for efficient thermal management. Early interest in this area focused on the fabrication of tooling (injection molding, electrodes for spark erosion, die casting *etc.*). Efficient cooling of tools and dies can reduce the cycle time which will reduce the part unit cost in a mass production operation. Using traditional manufacturing methods, however, cooling channels could only be drilled through molds in few key places and only in straight lines. This results in inefficient and uneven part cooling and potentially part distortion. The freedom of additive processes allows molds to be fabricated with internal cooling channels conformal to the mold surfaces in order to improve cooling efficiency, reduce cycle times and to equalize cooling/

shrinkage rates to improve part quality[17]. For some high throughput applications, the improvements in cycle time that can be realized amount to significant savings, notwithstanding the shorter lead times and lower costs typically associated with rapid tooling. The wider variety of additive processes capable of direct part fabrication coupled with freeform design capabilities has also led to a new interest in incorporating thermal management as a congruent consideration in many component designs. Recently, optimized mesh structures for high-surface area heat exchangers have been developed and manufactured using processes like LM and EB for a wide variety of applications such as automotive, aerospace and computer industries[18]. Another interesting example of this has been the additive fabrication of novel radio frequency (RF) structures. This has coincided with the development of process parameters for high thermal conductivity materials such as copper and copper alloys. Pure copper has a relatively high thermal conductivity (401 $W\ m^{-1}\ K^{-1}$ at 300K) which is ideal for thermal management applications. In the case of RF structures, a critical issue for high average power, high brightness photoinjectors is that they are currently limited to relatively low duty cycles. Efficient cooling through the utilization of conformal cooling channels built in, using direct metal additive manufacturing, can greatly reduce thermal stresses and result in high duty cycle and high gradient photoinjectors[19].

Integrated assemblies facilitated by additive manufacturing

Another opportunity facilitated by tool-less direct metal additive manufacturing techniques like EB is the direct integration of components such as pumps, fluid passages, and pistons into lightweight mesh structures. The direct integration of such components significantly decreases overall weight, optimizes mechanical properties, decreases fabrication time, decreases material waste, and decreases material costs. Work being done by the Materials Processing Group at Oak Ridge National Laboratories (Knoxville, TN) is utilizing additive manufacturing technologies to fabricate advanced robotic systems based on hydraulic and pneumatic actuation (Figure 3A), as well as a new class of lightweight, compact underwater robotic systems in which the robot base, hydraulic pump, reservoir, and accumulator are combined and integrated into a single lightweight structure (Figure 3B).

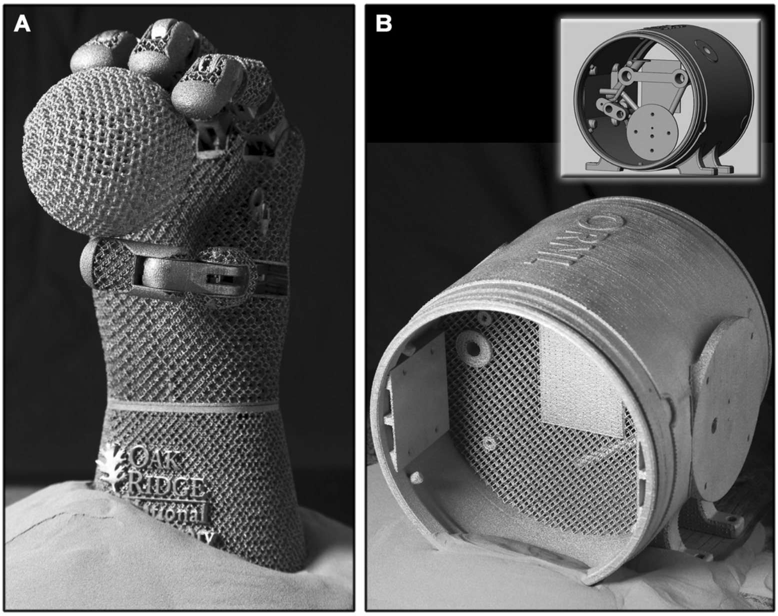


*Figure 3 Photographs provided courtesy of Oak Ridge National Laboratories (Knoxville, TN) showing **(A)** a lightweight robotic hand designed specifically for additive manufacturing using EB that utilizes stochastic network structures as well as hydraulic and pneumatic actuation. **(B)** Lightweight, compact underwater robotic system fabricated using EB in which the robot base, hydraulic pump, reservoir, and accumulator are combined and integrated into a single structure. The internal features are shown in the CAD model (inset).*

Applications of additive manufacturing in medicine

The medical implications of rapid prototyping and additive manufacturing were recognized very soon after the technologies became commercially available. Medical imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography are usually examined in a two-dimensional slice format. In the early 1990s in Europe, a consortium of companies and universities launched the Phidias project (after the Greek sculptor). This project focused on combining the software, hardware, machinery and materials to create accurate patient specific models from medical imaging data.

A key component in the development of patient specific treatments using additive manufacturing is to acquire accurate three-dimensional representations of the anatomy into a computer modeling environment for further manipulation. One of the results of Phidias was the development of software (Materialise, Belgium) capable of identifying and joining features from two-dimensional slices into three-dimensional computer models in stereolithography (.stl) format. Specific features (such as bones, organs, arteries *etc*.) can then be isolated and extracted based on contrast thresholding. Algorithms are used to convert the voxel data into a .stl surface model. Depending on the imaging technology used, the software can be used for the acquisition and reconstruction of skeletal and/or soft tissue geometry data.

Additive manufacturing in pre-surgical planning

In cases of severely abnormal anatomy, models fabricated with additive processes provide a tool for surgeons to better understand unique, intricate anatomical relationships that are difficult to visualize using two-dimensional images. Medical models have been widely used in maxillofacial and craniofacial reconstruction[20], as well as for the planning of complex distraction osteogenesis procedures for correction of severe deformities. In addition to being planning tools, three-dimensional, patient specific models are also often used to carry out rehearsals of new or complex procedures. Models can combine bony tissue data with high resolution MRI data (in which contrast is introduced into the vascular structure). Some of the most complex cases that have involved the use of 3D physical models derived from medical imaging data have been the planning of separation surgeries for conjoined twins. This presents significant challenges because of the complexities of the shared anatomy. One of the more extreme examples is the separation of craniopagus twins. These twins are joined at the cranium with two separate and individual brains but a shared vascular system. Starting in 2001 Medical Modeling (Golden, CO), fabricated numerous models of the patients anatomy, from vascularization to full scale models with simulated skin (Figure 4). The process took over a year and a half to plan, but ultimately the surgeries were successfully performed in 2003[21]. The use of 3D models fabricated with additive manufacturing processes proved to be an essential part of the surgical planning process and it is unlikely that cases such as this would be considered without them. Similar models have also been utilized on a more basic scientific level to improve the understanding of complex fluid dynamics in tissues and diseases such as an abdominal aortic aneurism (a permanent dilation of the aorta)[22]. Models made with additive processes have been used for both the direct study of procedures, as well as the experimental validation of finite element models.

Custom medical devices fabricated with additive manufacturing

Additive manufacturing is also being used for the direct creation of custom medical devices. An often referred to example is the additive manufacturing of custom fitted in the ear hearing aids. Traditionally, these devices would have been manually created by a skilled technician, but now waxy impressions are made of the patient's outer ear and three dimensional scanning is used to digitize the impression and the resulting CAD model is modified to accommodate internal circuitry. The models are then sent to an additive manufacturing machine for printing and delivery to the individual customers after the electronic components are installed[23]. This example also illustrates how additive manufacturing has facilitated the mass customization of a product.

Figure 4 *Photograph provided courtesy of Medical Modeling (Golden, CO) showing a model of the skull craniopagus twins, the bone and vasculature are different colors, and a window has been removed from the model to facilitate detailed examination.*

Additive manufacturing of orthopedic implants

With the recent improvements in direct metal additive processes like electron beam melting and selective laser sintering as well as the availability of some biocompatible plastics for additive manufacturing, there has been a great deal of interest in the direct fabrication of patient specific medical implants and devices. Titanium alloy, Ti6Al4V, is available for many direct metal additive processes and is often used in medical applications because of its biocompatibility.

One of the primary barriers to the practical implementation of direct metal additive manufacturing technologies has been attributed to the various regulatory agencies, particularly in the United States, but recently the US Food and Drug administration has approved the production of certain products fabricated using Arcam's EBM process[1]. Several companies, including Adler Ortho S.r.l (Italy), have been manufacturing standard, commercial sizes of acetabular cups for hip replacement surgeries using the Arcam electron beam melting process (Figure 5A). One of the primary benefits of using direct metal fabrication for a standardized part such as this is that engineered lattice structures which can be optimized for the specific requirements of the implant such as bone ingrowth surfaces can be incorporated and built into the parts. This eliminates several process steps associated with traditional manufacturing methods. In the case of these new implants, surfaces of the implant that come in contact with the bone have been optimized for osseointegration. According to Adler Ortho S.r.l, since 2007, over 15,000 of these units have been sold.

The same structural optimization concepts that have been applied to direct metal fabrication in the aerospace and automotive industry have also been utilized in the biomedical field, particularly for reducing the stiffness of orthopedic implants such as hip stems (Figure 5B) or limb sparing constructs. Skeletal tissues adapt to mechanical stimuli, adding bone where it is needed and removing bone where it is not needed. Typical hip stems are much stiffer than the host bone and, over time, this can cause stress shielding, bone resorption, and, potentially, the premature failure of the bone surrounding the implant. Additive processes allow the structure of the stem to be optimized to match the stiffness, or flexibility, of the host bone, reducing stress shielding[24].

Lattice structures fabricated with EB have also been utilized in a relatively new form of prosthetic attachment that involves the use of a transcutaneous osseointegrated implant. This is a bone anchored implant that breaches the skin barrier at the amputation site with an abutment that facilitates the attachment of prosthetic limbs directly to the skeletal system. For situations requiring load bearing prosthetic lower limbs, these osseointegrated implants have addressed many of the problems associated with traditional (socket type) prosthetics (Figure 5C). Recent studies have focused on the biocompatibility of these structures, both *in vitro*[25] and *in vivo.*[26]

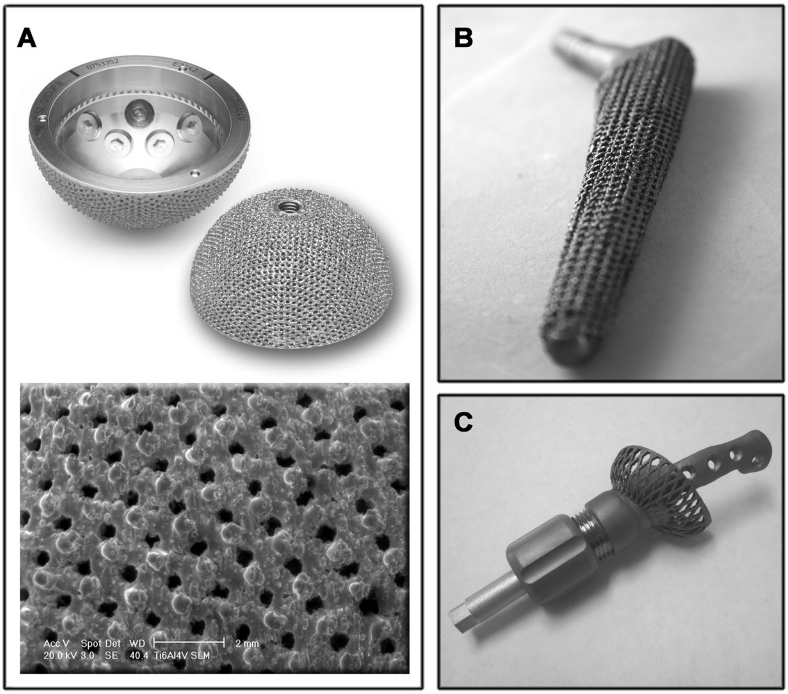


Figure 5 *Photographs showing several orthopedic implants fabricated using EB.* ***(a)*** *Acetabular hip cup with integrated bone ingrowth surface (photographs courtesy of Adler Ortho S.r.l, Italy).* ***(b)*** *Low stiffness hip stem implant optimized to promote bone ingrowth and reduce stress shielding.* ***(c)*** *Patient specific transcutaneous osseointegrated implant for the direct attachment of a prosthetic limb to the skeletal anatomy. The implants in B and C were fabricated at NC State University.*

Additive manufacturing in tissue engineering

The flexibility in geometries and materials that additive manufacturing accommodates coupled with precision computer control of the placement of those materials has given rise to a very interesting application; tissue engineering. The layered nature of additive manufacturing facilitates the generation of complex tissue scaffolds. The scaffolds are often in the form of porous implants designed to provide structural support for seeded/deposited living cells. The bounding geometry of the scaffolds themselves can be derived from patient specific medical imaging data to repair a specific wound, fracture, or defect (Figure 6).

To build such scaffolds a wide variety of biocompatible and bioresorbable polymers or ceramics can be used in conjunction with existing additive manufacturing systems. These include polymers like polymethylmethacrylate (PMMA), polycaprolactone (PCL), and hydroxyapatite (HA) composites. Another scaffold-like strategy is to encapsulate viable cells in hygrogels (hydrophilic polymer such as gelatin), which has been demonstrated for a variety of cell types. The encapsulated cells are then deposited using additive manufacturing. Much of the research associated with tissue scaffolds focused on the optimization of pore sizes, culturing and manufacturing methods (cold extrusion, inkjet printing, *etc.*). One of the greatest challenges to overcome is the difficulty in transporting nutrients through the scaffold. Cell mobility is also a key issue; the growth and proliferation of the cells is, after all, the objective. In the case of hydrogels, the retention of three dimensional geometries and proliferation of the cells through the cross linked polymer has posed significant challenges.

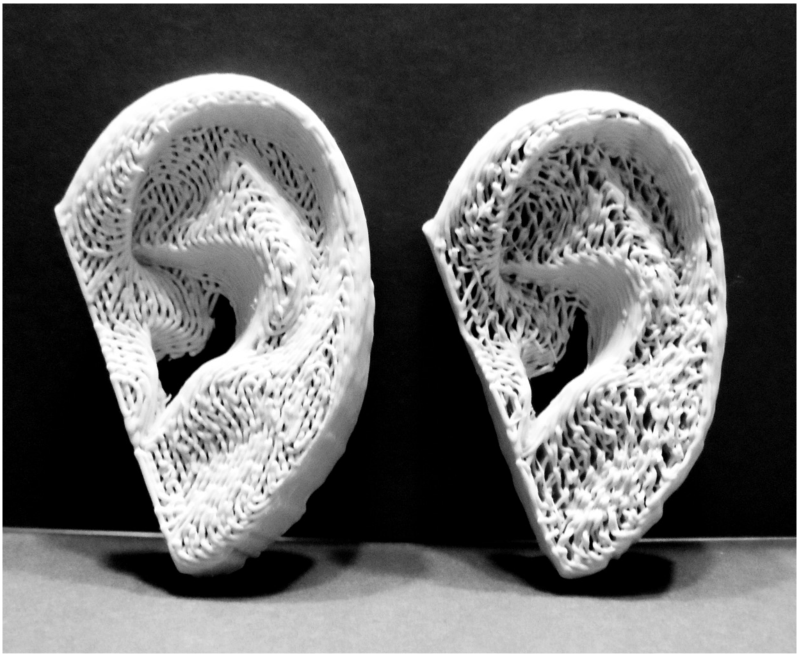


Figure 6 *Photograph showing tissue scaffolds fabricated at NC State University into the the patient-specific geometry of a human ear using an extrusion-deposition process. Such scaffolds can be seeded with autologous cells to reduce the likelihood of implant rejection.*

One possible solution is to eliminate the need for scaffolds in the first place. Congruent with research on the freeform fabrication of scaffolds, new techniques have been developed that facilitate the computer controlled, layer by layer deposition of living tissue cells. This represents the first steps towards the assembly and manufacture of biologically relevant and functional organs for transplantation in end stage therapies.

A key advantage is that these organs would be autologous, manufactured starting from the patient's own stem cells, therefore the risk of rejection would be greatly reduced. Three-dimensional organ printing also allows the precise positioning and placement of several differentiated cell types within a single construct. Recently regenerated bladders have been fabricated and implanted into human patients[28].

One of the challenges associated with this technology has been to maintain the efficacy of living cells throughout the positioning and deposition processes. Nakamura *et al*. has utilized commercial inkjet printing technology (low temperature, static-electricity actuated) with bovine vascular endothelial cells suspended in culture media in place of the ink. SEM analysis found that the printing process did not damage the living cells[29]. The next major hurdle has been to assemble cells into viable tissues. Research conducted at the Wake Forest Institute of Regenerative Medicine resulted in the inkjet printing of rectangular scaffold/cell constructs measuring roughly 8 x 6 x 4 mm (using human amniotic fluid derived stem cells and bovine aortic endothelial cells) and subsequently culturing and implanting them in mice. MRI evaluations were conducted at five, eight and 10 week time intervals along with surgical removal and subsequent histological/microscopic examination. Both the MRI and histological data showed post implantation vascularization of the tissue constructs[30]. Tissue constructs, however, have been relegated to relatively thin sections due in large part to the need for cells to access nutrients and dispose of waste via vascular pathways. In order to fabricate functioning tissues suitable for clinical application, a vascular network built within the tissue construct would then be necessary. The first steps have been taken in this direction with the demonstration that current additive processes are capable of printing complex intra-organ vascular trees and that the organization of specialized cells can be controlled with additive processes to produce vascular rings[31].

The ability to use inkjet printing and other extrusion technologies to place and deposit viable cells brings up an interesting notion: if it is possible to print living cells, then what about other materials? In fact, a wide variety of materials can be printed together with cells including specific chemical and pharmaceutical compounds designed to enhance cell proliferation and growth. The precise placement and deposition of functional compounds falls under the definition of a relatively new class of additive manufacturing collectively referred to as direct write technologies.

Direct write technologies

Although there are a great deal of similarities, direct write technologies are often differentiated from other additive manufacturing methods by the minute scale of the products and the wide variety of materials that can potentially be used. Direct write methods range from the use of inkjet (or other jetting technologies) to fine extrusion nozzles to nano-scale dip pen methods. Typically, direct write technologies are being utilized for the fabrication of features ranging from a few nanometers to a few millimeters. The materials used, usually in the form of specially formulated "inks" or slurries, often consist of nano-particles suspended in a solution. These materials can include polymers, ceramics, metals, and as we have discussed, biological agents. A far more extensive review of the diversity of processing modalities, materials, and applications is provided in the references[32]. The ability to use such a wide variety of materials is significant in that we are beginning to see direct write technologies utilized for the 3D fabrication of functional electronic devices. Like many of the other technologies that have been discussed, the fundamental challenges facing direct writing are associated with the limited number of materials that have been developed and investigated. While in theory a wide variety of materials can be used, there is a great deal of research and expense required for the development of each new material (each material must be combined with the appropriate mixture of solvents, binders, *etc*.) Yet, these technologies offer tremendous promise for the future as these challenges are transcended. Most direct write technologies are designed to deposit material on some form of substrate. When used in conjunction with macro scale additive processes it is conceivable that fully functional products can be fabricated. Already these technologies have been used to fabricate resistors, capacitors, conductive pathways, transistors, and semiconductors into complete functional circuits.

Near term outlook for additive manufacturing

Additive manufacturing has grown considerably in the past decade and it is beginning to gain traction as a viable process well beyond the simple tactile/visual models for which it was originally intended. This overview provides only a small glimpse of some of the fascinating applications that these technologies are being used for. How additive manufacturing will shape the future and how additive manufacturing will be utilized has been the subject of intense discussion, speculation, and a great deal of hyperbole. While additive manufacturing essentially frees designers, engineers, and scientists alike from many of the constraints associated with traditional manufacturing, it is still a developing technology and it is not yet a silver bullet. The freedom afforded by this technology also brings with it an entirely new set of challenges and constraints. Consider the resolution associated with the thickness of discrete layers, the surface roughness of components, poor dimensional accuracy, minimum feature sizes (*i.e.* thin walls, ribs, slots, *etc*.), and anisotropy associated with different part orientations. These are just a few examples of some of the new manufacturing constraints that will need to be considered. So far, unlike traditional DFM rules, not a great deal of attention has been given to these limitations. Of course, this is in part due to the fact that only now have these constraints become a critical issue for manufacturing. Standardization of these rules and processes will likely be a driving factor in the acceptance of additive processes as production tools. One recent development in this arena has been the formation of ASTM subcommittee F42 and ISO technical committee 261 on additive manufacturing technologies. So far the ASTM committee has published two documents. One ASTM F2972-12a standardizes the terminology for additive manufacturing technologies (a considerable achievement). The other, ASTM F2915-12, outlines a new file format that is intended to replace the STL format called the Additive Manufacturing Format (AMF). The STL format was an elegant solution for translating three dimensional CAD data into a series of discrete two dimensional contours that additive processes could produce (especially given the limited computational power available at the time). As we have discussed, the STL format approximates the surface geometry of a part with a series of interconnected triangular facets and little more. Modern additive manufacturing processes are making use of a wide variety of materials, colors, and compositions. The AMF format (V1.1) is seeking to address the requirements of new systems for multiple materials, functionally graded and even composite (mixed) materials. The AMF format also facilitates the inclusion of data regarding surface texture and engineered porosities. As was demonstrated earlier, the STL format has very specific shortcomings with regards to the accuracy of production quality components. The AMF has begun to address this by including the possibility of generating surfaces with curved "triangular" facets to improve part accuracy. Still, neither the AMF nor the STL format has a provision for carrying geometric dimension and tolerance data through the production process. Even if these data are not used directly by additive manufacturing processes, they are likely to play a critical role in any secondary post processing or finishing operations.

The finishing of parts fabricated by additive manufacturing, particularly direct metal parts, will become a significant challenge in the future. Clearly in some scenarios (such as the additive manufacturing of compressor blades that were discussed) this is not going to be the case. For small batch sizes, however, it appears that this is only starting to become apparent as more and more aerospace and automotive manufacturers begin to adopt and use selected AM components. The difficulty is one of quantities and flexibility. For most applications, direct metal additive manufactured parts can be considered near net shape components just like forgings and castings. However,unlike forgings or castings the production quantities for many AM parts are typically very small, so the hard automation and fixturing that was once used for finishing is no longer applicable or practical. Much of the effort in this area has focused on the improvement of the surface finish of AM parts, however, it is important to remember that surface finish is only one of many dozens of potential tolerance callouts. It is also clear that new finishing (machining /grinding/EDM) technologies will be required that make use of adaptive automation, measurement and fixturing; especially if solid metal components are integrated with functionally graded structures.

The issue of limited materials is also a key challenge looking forward. This is true both for polymer and metal based additive technologies, and several of the references that we have presented have cited the need for a wider variety of industrially relevant materials. At the same time it will be important for manufacturers to embrace the new material possibilities associated with additive manufacturing. The example of the ability to process Ti–Al using EB is a clear demonstration of this concept.

Another issue that has arisen in many of the works cited here is the relatively small size of the build volumes and long processing times for many AM processes. The processing time is often offset by the ability to manufacture unique geometries; however, the small build volumes still represent a significant barrier to the adoption of AM in many fields.

With that said, the wide range of fields in which AM is being adopted indicates that machinery manufacturers will continue to work to address these needs as the technology gains traction. One sector of the industry that is attracting significant attention lately has been additive manufacturing in the hobby market. As was discussed earlier, the price of some additive manufacturing machines has dropped so low that they can be purchased and operated by the general public (currently these systems range from a few hundred dollars up to about 5000 dollars)[33]. This has generated a great deal of excitement about the possibility of home-based 3D printing. Almost all of these low end AM systems are based on the extrusion of thermoplastics. To a large extent, the sudden appearance of low cost AM was facilitated by the expiration of key FDM® patents followed by the availability of a variety of open source CAD, STL, and slicing software platforms[1]. The ability for home users to access and/or create CAD representations of parts has already prompted alarms about the protections of IP, safety, and, of course, liability. Generally the quality of parts produced is lower than the quality expected from industrial machines; however, users are able to recreate a wide variety of parts and generate new innovations. While it is reminiscent of the file sharing controversy associated with the music industry, what remains to be seen is whether these "low end" systems will remain in the realm of hobbyists and educators, or if the technology will mature to a wider user base. Soon other patents will expire, however, extruded thermoplastics are particularly well suited for use by the home user. The raw materials are non-toxic, cheap, and easy to handle. The systems are also relatively simple and robust, which is not necessarily true for many of the other systems we have discussed. On the other end of the spectrum, the direct metal additive manufacturing systems are currently so extremely expensive that only a few manufacturing companies and select research groups are working with them.

The question of how mass customization and the decentralization/distribution of manufacturing will truly influence the economy, supply chain networks, and even the environment is yet unanswered. What is clear is that the growing field of additive manufacturing has opened up numerous applications that were never before possible and despite the many shortcomings and challenges, it is clear that in the coming years it is likely that additive processes will play an ever growing and important role.

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