Perspectives on Additive Manufacturing

David L. Bourell

Department of Mechanical Engineering, The University of Texas, Austin, Texas 78712; email: dbourell@mail.utexas.edu

Keynote Topic

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Abstract

Additive manufacturing (AM) has skyrocketed in visibility commercially and in the public sector. This article describes the development of this field from early layered manufacturing approaches of photosculpture, topography, and material deposition. Certain precursors to modern AM processes are also briefly described. The growth of the field over the last 30 years is presented. Included is the standard delineation of AM technologies into seven broad categories. The economics of AM part generation is considered, and the impacts of the economics on application sectors are described. On the basis of current trends, the future outlook will include a convergence of AM fabricators, mass-produced AM fabricators, enabling of topology optimization designs, and specialization in the AM legal arena. Long-term developments with huge impact are organ printing and volume-based printing.

1. INTRODUCTION

1.1. Additive Manufacturing

Additive manufacturing (AM) is defined by the joint ISO/ASTM terminology standard to be the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (1). The salient part of the definition is use of a computer to translate a solid model into a real part. The technologies represented by AM are the 3D analog to ubiquitous 2D printers. This similarity of AM to 2D printing has given rise to the alternate common name of 3D printing. Indeed, over the last 30 years of modern AM, there have been a plethora of appellations: additive fabrication, additive processes, additive techniques, layer manufacturing, freeformed fabrication, rapid tooling, additive layer manufacturing, solid freeformed fabrication, rapid prototyping, rapid manufacturing, direct digital manufacturing. The term additive manufacturing was formally adopted on January 14, 2009, in West Conshohocken, Pennsylvania. The 59 attendees at this inaugural meeting of the ASTM F42 Technical Committee on Additive Manufacturing had earlier voted to form an ASTM technical committee to develop standards for AM, but a name was needed for the committee. A number of names for the technology, including 3D printing, were discussed. Opposition to referring to the technologies as 3D printing focused on a specific binder jetting process invented by Cima, Sachs, and others at MIT that they termed 3D printing (2). It was considered undesirable to relabel all the technologies with the name of a single one. The ASTM committee vote was in favor of AM, and over the next few years, this term caught on. AM was shortly thereafter embraced by the ISO Technical Committee TC261, which contributed to its international adoption.

Today, both AM and 3D printing are used, but generally in different circles. The former term is used by the technical community, whereas the general public largely uses the latter. 3D printing is typically the nomenclature of mass media, marketers of the technology, and decision makers, although it is notable that US President Obama in stump speeches and several State of the Union addresses in the 2012–2014 time period used the term AM instead of 3D printing. Even within the AM technical community, there has been an evolution of the term 3D printing from the MIT binder jetting process to include all low-cost AM fabricators, regardless of the fabrication technique.

There are broadly two schools of thought on the future of the terminology. One is that 3D printing with its large base of popularity will envelop AM, and the latter term will disappear. However, this author's opinion is that the two terms will continue to exist side by side within their spheres of influence. This is not unheard of in manufacturing. Consider lost wax casting, the common term for a casting process that the technical community refers to as investment casting. Or, consider metal inert gas (MIG) welding as it is referred to by operators, whereas the engineers often term the same process gas metal arc welding. It is quite possible that both AM and 3D printing will survive similarly, with the former term embraced by the technical community and the latter by the public.

1.2. Growth of the Field

According to the *Wohlers Report 2015* (3) (**Figure 1**), the AM industry has skyrocketed in value from 2010 to 2015, with an annual growth rate of approximately 30%. Material sales show a comparable growth (**Figure 2**). With the exception of a dip associated with the Great Recession in 2008–2009, material growth has been strong. According to the marketing research firm IDTechEx, material sales are projected to increase to $8 billion by 2025 (4).

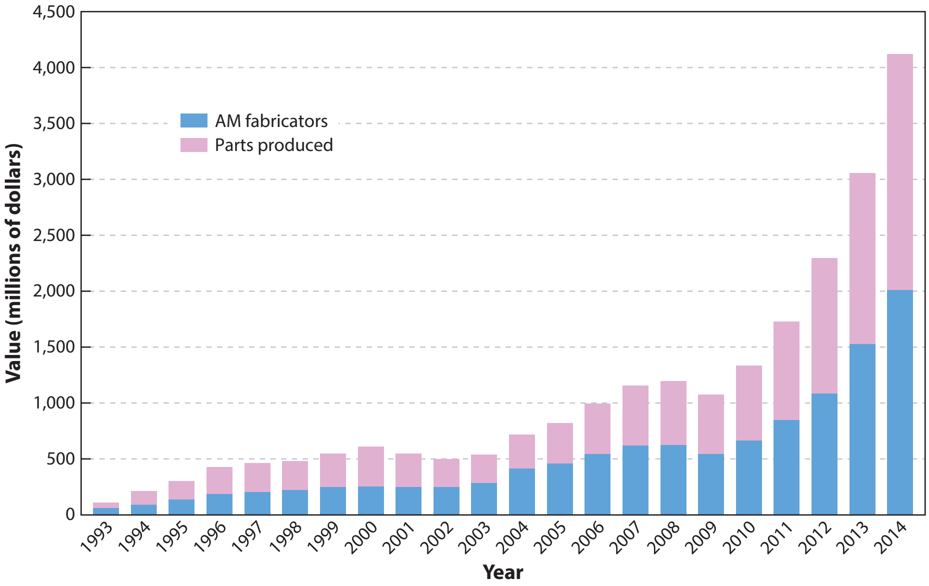

Figure 1

Growth of AM worldwide from 1993 to 2014 in terms of the value of AM fabricators (*lower bars*) and parts produced (*upper bars*). Adapted with permission from Reference 3.

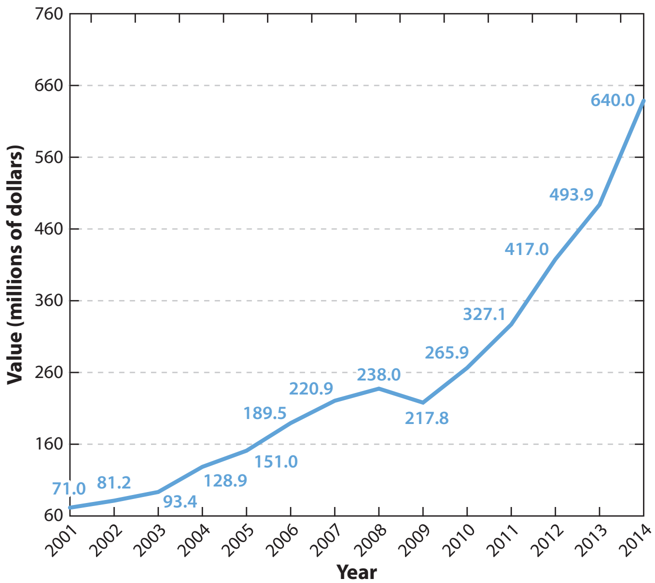

Figure 2

AM feedstock material sales worldwide for the period 2001–2014. Adapted with permission from Reference 3.

A number of interrelated factors have contributed in varying degrees to the explosive growth of AM technologies commencing in 2010. First was the development of truly low-cost AM units. The harbinger was Malone & Lipson's Fab@Home unit (5). A growing number of hobbyists and do-it-yourselfers adopted the technology. A transition then occurred from this small group to the general public. The expiration of founding patents, particularly those on low-cost AM units, allowed competing entities to enter the marketplace. There was an explosion of low-cost material extrusion fabricators purchased by the general public, leading to what has sometimes been dubbed the Makerbot craze (6), named after one of the popular low-cost printers. Development of cheap or free, easy-to-use computer 3D modeling software has also contributed to the growth of AM. Programs such as Google Draft have enabled the public to create virtual 3D parts. 3D clip art sites such as Shapeways provide users with the capability to either purchase 3D parts or download images. iPhone applications such as Autodesk's 123D Catch allow a user to convert multiple 2D photos of a person or object into a 3D printable file. Creation of useful 3D parts virtually drives a desire in many cases to actually produce a hard copy of the part, leading to a demand for AM. President Obama in March 2012 announced a vision to create multiple US Manufacturing Innovation Institutes (MIIs) (7). The first MII was funded and established later that year with a theme of AM. Obama reported on the MII in general and AM specifically in two State of the Union addresses in 2013 and 2014 (8, 9). This publicity at the highest level of government has resonated internationally with private industry, government labs, academia, and foreign governments, resulting in significant investment of time and resources to developing AM.

1.3. Economics of AM and Current Markets

A driving feature of any manufacturing process adoption is the cost of parts produced. One such equation for calculating the cost C_{p} of a manufactured part or component is (10, pp. 409–10)

$$C_{\mathrm{p}} = \begin{matrix}\text{material}\\ \text{cost}\end{matrix} + \begin{matrix}\text{tooling}\\ \text{cost}\end{matrix} + \begin{matrix}\text{equipment}\\ \text{cost}\end{matrix} + \begin{matrix}\text{overhead}\\ \text{cost}\end{matrix}.$$

$$C_{\mathrm{p}} = \left(\frac{P_{\mathrm{m}}\rho V}{1-f}\right) + \frac{C_{\mathrm{T}}N_{\mathrm{T}}}{n} + \frac{1}{\dot{n}}\left[\frac{C_{\mathrm{C}}}{Lt_{\mathrm{wo}}}\right] + \frac{\dot{C}_{\mathrm{oh}}}{\dot{n}}. \qquad 1.$$

Here P_{m} is material cost on a mass basis, ρ is material density, V is part volume, f is fraction of material that is scrapped during manufacturing, C_{T} is cost for (dedicated) tooling, N_{T} is the number of complete tool sets needed for the production run, n is the number of identical parts desired (the production run), $\dot{n}$ is the rate at which parts are manufactured (the production rate), C_{C} is the cost of (permanent, nondedicated) equipment, L is the time load (the fraction of the total time during which parts are being produced), t_{wo} is the write-off time (the lifetime of the equipment), and $\dot{C}_{\mathrm{oh}}$ is the overhead cost rate normalized to part production time.

As Equation 1 shows, there are four components to the part cost. With respect to AM processes, the following is noted. (*a*) As there is no tooling, the tooling term vanishes (i.e., $C_{\mathrm{T}} = 0$). (*b*) The production rate $\dot{n}$ is generally very low for AM processes compared with that for traditional manufacturing processes. The last two terms are inversely related to $\dot{n}$, which tends to make their contribution large for AM processes. (*c*) For high-end AM processes, the equipment cost C_{C} is large. Coupled with the low production rate, the equipment cost term often dominates the part cost for service parts. (*d*) The material cost P_{m} for AM is often large compared with that for traditional manufacturing processes.

Economic selection of a manufacturing process may be accomplished by comparing the cost to produce a part using two (or more) manufacturing processes. A common approach is to plot

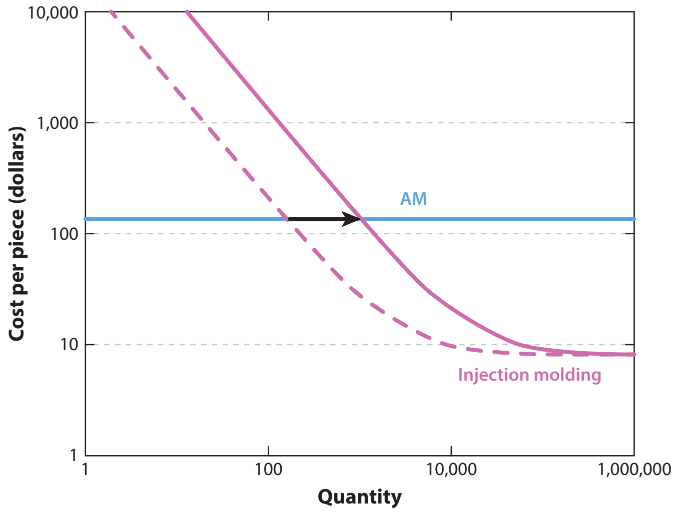

Figure 3

A plot based on Equation 1 and showing the cost to produce a part as a function of the number of identical parts needed in the production run, using the case of a 1-kg polyamide part. Shown are typical curves for AM (*blue*) and injection molding (*purple*). The shift of the injection molding curve to the right (denoted by the *arrow*) is associated with an increase in part geometric complexity. The intersection of the injection molding curve and the AM line marks a break-even production run below which using AM is more economical.

the part cost C_p as a function of the number of parts n in the production run. **Figure 3** shows an example of this approach for a generic 1-kg polyamide part that has reasonable geometric complexity and that is produced using laser sintering or injection molding. As Equation 1 shows, the AM part cost does not depend on the number of parts produced n, so the line is flat. In contrast, if the part is produced using injection molding, an expensive (i.e., large-C_T) die set must be produced prior to running any parts. The effect of this large cost component is embodied in the tooling cost term in Equation 1. Because the number of parts produced n appears in the denominator of the tooling cost, there is an inverse relationship (demonstrated by the dotted line in **Figure 3**). The intersection of the cost curves represents the break-even production run for the two manufacturing processes, in this case just over 100 parts. AM produces cheaper parts when the total number of parts needed is less than this break-even number, and injection molding is cheaper for larger production runs. From these considerations, one may generalize the rule of economics for AM: AM processes find application in areas in which the production numbers are low.

It is possible to quantify the part geometric complexity in the example shown in **Figure 3**. As the part geometry becomes more complex, the cost of the tooling for injection molding the part increases. This increase results in an upward vertical shift of the injection molding curve (solid line), which moves the break-even cost to the right to a larger value. The rule of economics for AM parts may then be modified to be: AM processes find application in areas in which the production numbers are low and in which the part geometries are complex.

On the basis of this analysis, some observations may be made with respect to widening the application space for AM processes. On the basis of Equation 1 and as illustrated by **Figure 3**, the AM application space may be widened by moving the break-even production number to the right. It has already been noted that increasing part geometric complexity accomplishes this goal. It is also possible to effect this change by lowering the AM line. Upon examination of Equation 1, ways to achieve this change include lowering the material cost P_m, reducing the scrap fraction f, lowering the cost of the AM fabricators C_C, and increasing the production rate $\dot{n}$. All of these approaches have been and are being researched and developed. The effect will be not only increased productivity but also widening of the application space by making AM more economically viable relative to other manufacturing processes.

The AM field was born in the automotive industry as a means of rapid prototyping (e.g., Reference 11). In fact, the field was referred to as rapid prototyping until the early 1990s. The main benefit was accelerated generation of form-and-feel objects that reduced the design cycle for new vehicles. The day or two required for rapid prototyping was in contrast with the time interval between submission of a prototype request to a model shop and receiving the part, often 1–2 months if there was a backlog (12). One might then conclude that, presently, AM is extremely fast for prototyping but extremely slow for manufacturing.

With regard to current market applications of AM, the common feature is production of geometrically complex parts in low production numbers. Automotive applications are limited to prototypes, tooling, and jigs/fixtures. AM is generally not used in automotive production, because the production runs are too high to be economically favorable. Annual worldwide automobile production currently exceeds 50 million vehicles, an extremely large number even when broken down by model (13). In contrast, AM is being integrated into after-market customization and low-production-run vehicles. For example, Bentley Motors produces fewer than 5,000 customized cars annually, and AM parts are being used on these vehicles (14).

Aerospace application of AM is quite different from automotive application in terms of production numbers. Although each commercial aircraft contains millions of parts, such aircraft are produced in small production numbers. As an example, consider the Boeing 747 (B747), one of the most successful commercial planes. The first B747 was produced in 1969, and the plane is still in production, with the most recent sale in May 2015 (**http://www.airfleets.net/listing/b747-1-lnasc.htm**). The total number of B747s sold over this 46-year interval is just over 1,500 planes, averaging fewer than 35 planes annually. Because of certification and reliability issues, the integration of AM into aerospace production has been slow but steady. The Boeing 787 Dreamliner is flying with approximately 30 AM parts (15).

Other fields in which AM is making headway in service part production include medicine (implants and prosthetics), tooling, art, jewelry, museum displays and architecture, and game avatars (3). All share the common theme of being geometrically complex parts produced in low production numbers.

2. AM PROCESSES

The ISO/ASTM terminology standard (1) categorizes all AM processes into seven broad categories. Definitions below in quotes are taken essentially verbatim from the standard.

Binder jetting is "an AM process in which a liquid bonding agent is selectively deposited to join powder materials" (1). The modern AM process was invented by Sachs et al. (2) at MIT and was termed 3D printing. Soligen was an early spin-off company whose primary product was casting cores. All types of powder materials may be joined by the binders, although the mechanical properties are compromised unless postprocessing is done to remove/convert the binder, followed by some type of sintering or infiltration. One key feature of current binder jetting processes is the ability to create colorized objects by using color-ink-jet technology on the binders.

Directed energy deposition is an AM process "in which focused thermal energy is used to fuse materials by melting as they are being deposited. Focused thermal energy means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited" (1). The earliest commercialization was the LENS® process developed at Sandia National Laboratories in the late 1990s (16). This development was preceded by that of Weiss et al. (17), who used a thermal spray approach with a series of masks. Current processes generally use a laser beam energy source.

Material extrusion "is an AM process in which material is selectively dispensed through a nozzle or orifice" (1). For most commercial devices, the material is a polymer or polymer-based material that is heated and flowed through a moving orifice to create the part. The technology was first developed and marketed by Stratasys, founded by Scott and Lisa Crump in the late 1980s. Due to the relatively inexpensive machine components, material extrusion has become a strong leader in low-cost AM fabricators. Another approach with material extrusion is to use flowable slurries without heating. The Fab@Home and related printers operate on this principle. It is possible to extrude food items such as icing and cookie dough (18). A number of biomedical cell printers use this approach, with large-diameter nozzles to minimize shear loading on the cells as they are deposited to enhance cell viability. One of the early cell printers was the EnvisionTEC 3D-Bioplotter, used in research at Mülhaupt's lab at the University of Freiburg (19).

Material jetting is "an AM process in which droplets of build material are selectively deposited. Example materials include photopolymer and wax" (1). Objet Geometries was founded in 1998, and a primary technology was based on the invention by Gothait (20). The approach is to deposit photopolymer droplets onto a build surface that is bathed in UV light to achieve curing.

Powder bed fusion is "an AM process in which thermal energy selectively fuses regions of a powder bed" (1). The energy source is a laser or electron beam. The process was first commercialized by Deckard (21) and Beaman through DTM Corporation. DTM was acquired by 3D Systems in 2001. The electron beam technology, popular for metal powder processing, was commercialized by Arcam.

Sheet lamination is "an AM process in which sheets of material are bonded to form an object" (1). In 1985 Michael Feygin founded the first AM company, Helisys. Laminated object manufacturing (LOM) was based on a stack-and-cut approach wherein paper was glued to a previous layer followed by laser cutting. In 2003, Mcor Technologies developed a similar technology based on a tungsten-tipped blade cutter.

Vat photopolymerization is "an AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization" (1). Chuck Hull cofounded 3D Systems with Raymond Freed in 1986, with a focus on stereolithography (22). Several versions of stereolithography had been separately published earlier by Munz (23), Kodama (24), and Herbert (25). The first modern commercial AM machine was the SLA-1, introduced in 1987, with the first machine sold in 1988.

3. HISTORICAL DEVELOPMENTS

The author is aware of two historical accounts of AM. The first (26, pp. 6–19) describes layered manufacturing in broad terms dating back to the 1860s and based largely on US patent literature. The second (27) details developments in modern AM starting in 1987 with the introduction of the first modern AM machine by 3D Systems.

One might divide a history of AM into three eras: prehistory, precursors, and modern processes. AM prehistory includes three technological developments dating back ∼90–150 years: photosculpture, topography, and material deposition. The AM precursors are processes that included most, if not all, of the features of AM processes but that, being invented before widespread societal acceptance of distributed computing (circa 1984), were never commercialized. Modern AM processes were invented (or in some cases reinvented) and were successfully brought to commercialization.

3.1. AM Prehistory

Photosculpture, topography, and material deposition are three technologies that use toolless manufacturing approaches to construct parts in an additive fashion. Because these approaches peaked long before the invention of the computer, they relied on manual labor to form layers or subcomponents that were then assembled by hand.

3.1.1. Photosculpture. The earliest of the three AM prehistorical processes was photosculpture, successfully demonstrated in Paris by François Willème as early as 1860 (26, pp. 6–19; 28). Using newly invented photography, a subject was positioned in a room and simultaneously photographed 360° by using 24 equally spaced cameras (**Figure 4**). Silhouettes from each photo were used by hand craftsmen to produce sections of the sculpture that were then assembled and finished to form

Figure 4

Willème's Paris photosculpture lab in which subjects were photographed, circa 1860. Shown here is Admiral David Farragut, hero of the Civil War. Reproduced with permission from the George Eastman House, Rochester, NY.

Figure 5

A section of Willème's Paris art studio in the 1870s, showing various photosculpture art pieces. Reproduced with permission from the George Eastman House, Rochester, NY.

the full sculpture. A photograph from Willème's studio is shown as **Figure 5**. Others advanced the technique, using photosensitive expanding gels (29) and light banding to create contour lines (30).

A current version of photosculpture is 123D Catch by Autodesk (**http://www.123dapp.com/catch**). This software is available on a variety of platforms, including the Android, iPhone, and personal computer (PC). The subject is still while a photographer walks around the subject taking photos. The photos are stitched together using the software's image recognition features, and the result is a 3D rendering of the subject. These renderings may be converted to printable AM files.

3.1.2. Topography. Topography is based on either cut-and-stack or stack-and-cut approaches using a flat feedstock. This approach dates to the Blanther patent of 1892 (31). Blanther's invention was the creation of 3D tools for pressing raised paper topographical maps from aerial photos. The technique, shown in **Figure 6**, involved laying wax sheets over the aerial photograph and cutting along the constant elevation lines. The pieces were then stacked to create a full top and bottom die set that was then smoothed and backed. Paper was pressed between the tools to create a 3D image. Emphasized here is that the AM reference is to the tool set, not to the final paper product. Similar approaches for topographical applications were advanced over approximately the next 75 years (32–34). Later developments focused on laminated creation of tooling. Matsubara (35) used a photosensitive resin mixed with refractory powder and formed into a sheet. Each sheet was

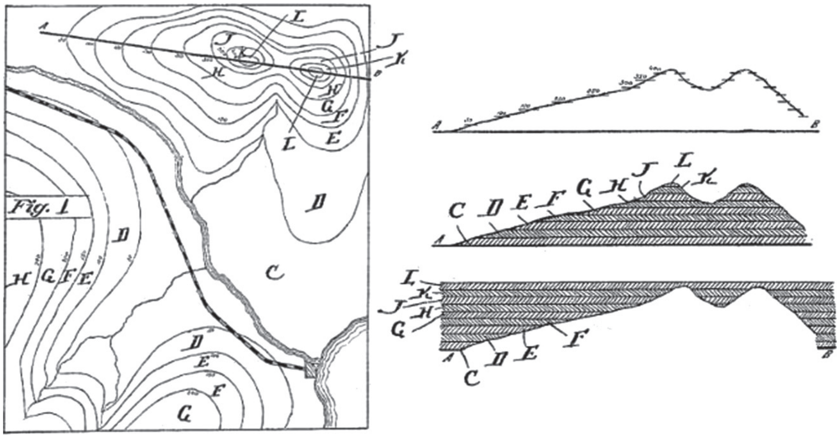

Figure 6

The earliest topographical layered manufacturing, from Blanther (31) in 1892. The images are a topographical map showing isoelevation lines (*left*) and a wax tool set and molded paper 3D map (*right*) obtained by a cut-and-stack approach. Reproduced with permission from Reference 31 (source: United States Patent and Trademark Office, **http://www.uspto.gov**).

selectively exposed to light to create cross-linked layers that were later stacked. The application was casting mold components. DiMatteo (36) machine cut sheets of material including metal that were then stacked with the aid of registration holes on each sheet. This approach was advanced in the 1980s by Nakagawa and colleagues (37–39) at the University of Tokyo for the production of forming tooling. Modern AM technologies based on this general approach are all the sheet lamination approaches described in Section 2.

3.1.3. Material deposition. With material deposition, a moving deposition source applies material at a usually constant rate. By moving the source or the object manually, 3D parts can be created. The earliest identified example in the patent literature was provided by Baker, who in 1925 proposed a moving weld head to create ornamental welded parts (40). **Figure 7** shows several exemplar parts. Starting in the 1960s, there were a number of inventions that involved point-wise deposition onto a rotating axis or mandrel (41–45). Although these inventions are rather limited in terms of the geometries that could be produced, they demonstrate both the point-wise creation of useful parts and the fuzzy interface between AM and traditional processes, including hard facing and multipass welding.

Perhaps the current AM process closest to the original Baker work of 1925 is the 3Doodler (**http://the3doodler.com/**). The 3Doodler is a handheld pen that extrudes plastic through a nozzle at a given rate. The user moves the pen relative to the object to create a part. Other closely related technologies are the material extrusion, material jetting, binder jetting, and directed energy deposition approaches.

3.2. AM Precursors

AM precursors were manufacturing processes that had all the features of modern AM technologies but lacked an intuitive computer interface required for truly arbitrary part generation by a knowledgeable but non-computer-expert operator. These precursor technologies date from the

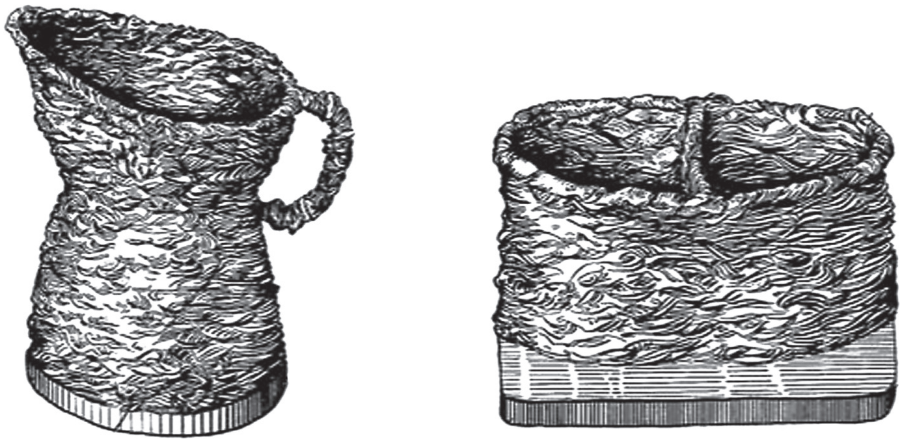

Figure 7

Metallic objects built on a plate by weld deposition. Reproduced with permission from Reference 40 (source: United States Patent and Trademark Office, **http://www.uspto.gov**).

1950s to the mid-1980s. The key date of transition from precursor to modern AM processes was 1984, the year Apple released the Macintosh (Mac), the first PC with an intuitive graphical user interface. Over an astonishingly short period of time—a few years—personal computing became ubiquitous in developed societies worldwide. Prior to this, PCs had already existed. In fact, IBM had $4 billion in sales in the PC market in 1984. The Mac, though, was intuitive and operated graphically without the need to learn a programming language. IBM followed suit in 1985 with the introduction of its Windows operating system. The computer in AM is crucial not only for driving and controlling the fabricator but also for providing a user-machine interface for virtual part creation, situation, and modification prior to fabrication.

The earliest precursor process was a process similar to stereolithography and was invented by Munz (23) in 1956. Included in his system was a method for layer-wise exposure of photosensitive polymer emulsion, including a piston that was lowered between layers. Ciraud (46) disclosed in France in 1972 a powder process that is essentially directed energy deposition. Metal powder was directed into a localized heat source (laser, electron beam, plasma source) and melted to build up the part (**Figure 8**). Swainson (47) patented a process involving crossed lasers for part creation. The part was created at the intersection of the lasers by either photochemical cross-linking or chemical degradation. This approach was never reduced to practice. Kodama (24) published the first functional photopolymer AM system based on photopolymers. Included were three approaches: a top-down masking approach, a bottom-up masking approach, and a moving light source on an *x-y* gantry. Herbert (25) developed a similar photopolymer approach at 3M. He used a laser point source with optics mounted on an *x-y* gantry. The photopolymer was exposed in a container at ~1-mm-layer thicknesses.

Housholder (48) described several approaches for freeformed creation of molds, including a process of laser sintering. One embodiment involved selectively scanning a powder bed surface with a laser beam. The powder could be plastic or sand mixed/coated with plastic. The laser system could be computer controlled, and successive layers were added, with the process repeated to build up the part.

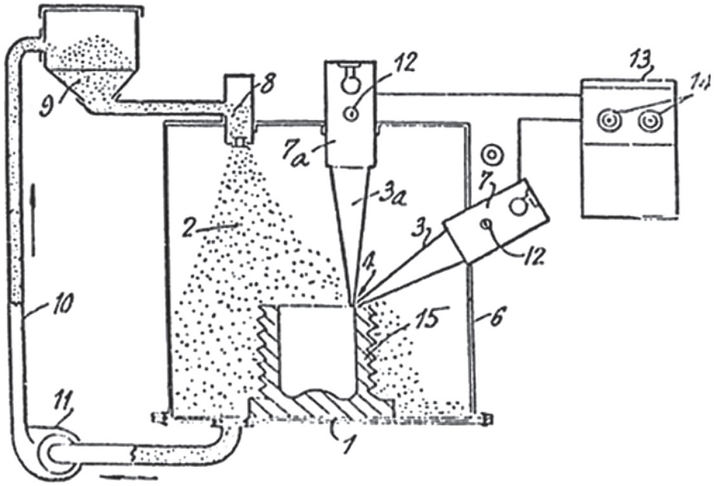

Figure 8

Early description of directed energy deposition from Reference 46. Among the items shown are powder deposition (item 2), energy sources (items 7 and 7a), and the part being built (item 1). Reproduced with permission from Reference 46.

3.3. The First Modern AM Companies and Sales

As mentioned above, the first modern AM company was Helisys, founded by Feygin in 1985 (26, pp. 6–19). The primary product of Helisys was LOM, a sheet lamination process. The first LOM machine shipment was in 1991, and the company closed in 2000. The Denken venture in Japan started in 1985, but it did not introduce its first stereolithography machine, the SLP-3000, until 1993.

As mentioned above, Hull and Freed formed 3D Systems in 1986, and the first modern AM machine, the SLA-1, was introduced in 1987, with the first sale occurring in 1988. Crump founded Stratasys in 1988, with the first shipment of a fused deposition modeling (FDM) fabricator in 1991 (26, pp. 6–19). DTM was founded in 1987 and shipped the first commercial laser sintering machine in 1992. From 1990 to 1993, DTM operated as a service bureau for laser sintering. Soligen was the first company based on binder jetting and operated as a service bureau. It was founded in 1991, with the first parts shipped in 1993. With respect to directed energy deposition, LENS® technology was initiated at Sandia Labs in the early 1990s and was later transferred to Optomec. The first machine shipment was in 1998. More information on developments in modern AM processes to the present is available in References 26 (pp. 6–19) and 27.

4. OUTLOOK

4.1. Convergence of AM Fabricators

A 1998 roadmapping study provided insight into the future outlook of AM (49). A summary figure from this study is reproduced as **Figure 9**. It shows that AM (termed rapid prototyping in 1998) technologies were rather unified in 1998 and predicted that a trifurcation of processes would occur in the future. What is shown as design verification systems in **Figure 9** is today termed low-end AM or 3D printers. These are machines produced in high volumes for prototype applications.

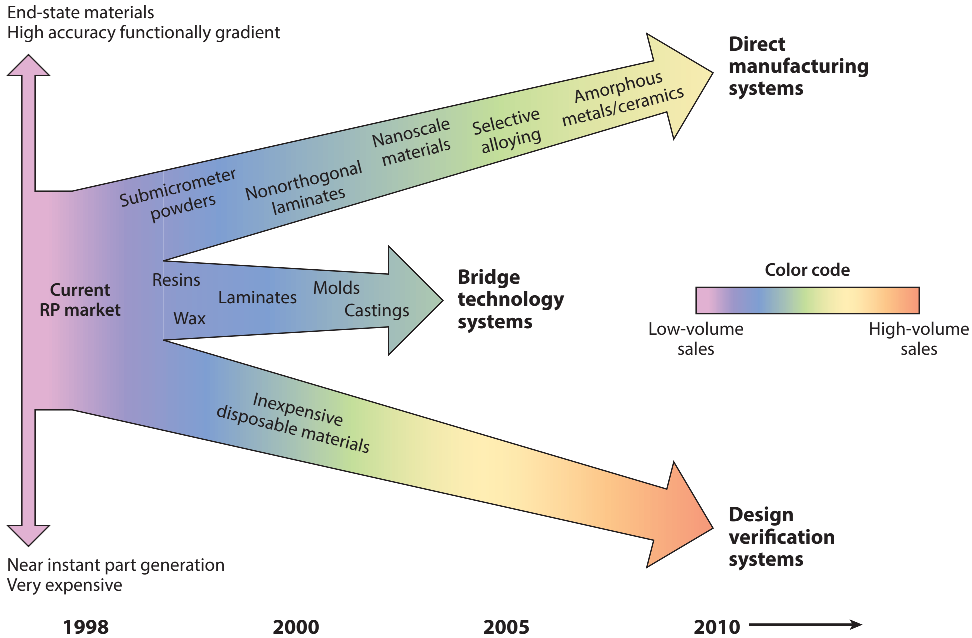

Figure 9

A 1998 prediction of the development of AM over the period 1998–2010. The shown trifurcation depicts the development of low-volume, high-end AM fabricators; high-volume, low-cost AM fabricators (3D printers); and bridge technologies that convert the materials from low-end printers to commercially viable materials. Adapted with permission from Reference 49.

What is referred to as direct manufacturing systems in **Figure 9** is known today as high-end or production AM fabricators. These are expensive machines that produce service parts with specific properties suitable for the intended application. The specific examples listed in **Figure 9** have not been commercially realized to a large degree, but the trend is accurate. The term bridge technology systems in **Figure 9** describes what today might be referred to as a conversion technology. This group of processes, not AM, is designed to transform the material of a low-end AM processed part into a material with structure and properties suitable for service applications. The common approach was to use the AM part as a pattern for the generation of a mold or tooling. In a broad sense, the predictions have been realized. There are high-end and low-end printers that appeal to different audiences, and conversion technologies are in place.

This author contends that over the next 10–15 years there will be some degree of convergence between the high-end and low-end AM fabricators. Several factors will contribute to this convergence. First, the cost of at least some high-end fabricators will come down due to the expiration of founding patents, increased demand for service parts, and increased competition from new enterprises entering the marketplace. A possible example is HP's Multi Jet Fusion® technology, which is scheduled for market release in 2016 (**http://www8.hp.com/us/en/commercial-printers/floater/3Dprinting.html**). A second contributing factor will be a similar transition in cost of feedstocks for high-end machines. Increased demand for feedstock will spur new companies to enter the material marketplace. Examples are Advanced Laser Materials in Belton, Texas, and Structured Polymers in Austin, Texas. Higher-volume demand may also result in a shift to more economical, higher-volume production methods by existing feedstock providers that could result in a reduction in feedstock cost for the consumer. Finally, research and development will be increasingly focused on low-end printer machines, processes, and feedstocks. The result will be a larger palette of products with improved finish and performance characteristics.

4.2. Mass Production of AM Fabricators

A general conclusion from Section 1.3 is the well-known manufacturing principle that the cost of an item decreases as the planned production run increases. This principle is also true for AM fabricators, which are themselves fabricated largely using conventional manufacturing methods. To date, virtually no AM fabricators have been designed for large-scale production, and the price points for the fabricators reflect this reality. One might compare a moderately priced 2D multifunctional machine (that can copy, scan, fax, and print) with any of the popular commercially available low-end 3D printers. The former is considerably more sophisticated in terms of mechanisms, functionality, and performance, but the cost is perhaps as low as 15–20% that of a comparably sized 3D printer. A significant reason for this apparent contradiction of cost and value lies in the fact that the 2D printer was designed for high-volume sales, whereas the 3D printer was not. HP's announced entry into the AM landscape in 2014 is a harbinger signaling the beginning of a new era of AM. If HP is successful, the AM marketplace will grow. It becomes foreseeable that other large multinational companies will enter the field. The ultimate benefit to users will be low-cost machines producing high-quality parts. Given the economic considerations in Section 1.3, lowered AM fabricator cost will directly impact AM part cost.

4.3. Topology Optimization

Topology optimization is a part design methodology based on computational analysis of the service requirements. In a typical application, one might use topology optimization to create a part that carries a prescribed traction while minimizing the part mass or volume. In this case, a computational approach might be to start with a large, virtual, volume-filling slab of material. The tractions are applied, and a finite element analysis identifies volume elements in the slab that carry little or no stress. These elements are computationally removed from the slab, and the process is repeated, generally multiple times. The final result is a part that safely withstands the tractions with minimum mass or volume and that generally has all volume elements contributing significantly in terms of the resultant stresses. **Figure 10** shows a virtual stress representation of a topology-optimized piston head and the final topology-optimized part. As seen here, topology-optimized parts are typically geometrically complex, which makes them suitable for fabrication using AM technologies. In this instance, AM is an enabling technology for topology optimization. There is therefore a strong synergism between topology optimization and AM, and this synergism is predicted to develop and grow in the coming years.

4.4. Legal Aspects

As is the case with any new manufacturing process entering the marketplace in a significant way, disputes will arise at all stages of the machine and part life cycle. Attorneys specializing in AM issues are already appearing, and this trend is anticipated to increase as AM technologies evolve and grow. In some cases, there will be a significant amount of prior case law to apply. Examples might be patent infringement issues between existing and new original equipment manufacturers and copyright infringement in which a 3D design is copied without permission. AM product liability has the potential to plow new ground in the legal system. It is typical in product liability to be able to identify a single manufacturer of a part or product, and this single entity is usually responsible

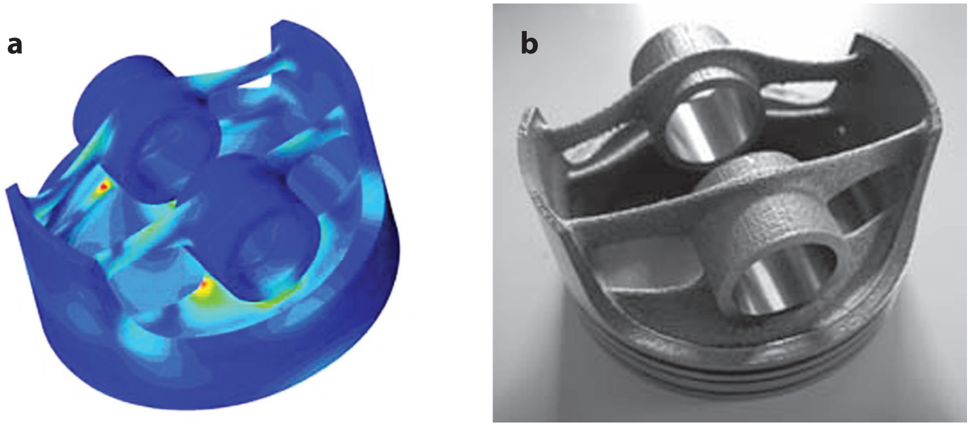

Figure 10

Piston topology optimized in solidThinking Inspire. (*a*) The computer-generated, topology-optimized stress field indicating largely uniform internal stress on loading. (*b*) The topology-optimized part. Figure reproduced with permission from Nick Hardman, owner of HardMarque, Australia (**http://www.hardmarque.com/**).

for the design, manufacture, and distribution of the part or product. This is not necessarily the case with AM, which has the potential to distribute manufacturing (see, for example, Reference 50). The potential is that the chain of identification of an AM part will be completely lost prior to the part going into service.

Another issue facing the legal community is the manufacture of undesirable parts. The paradigm is Wilson's 3D printed gun (51). As Johnson states, "Law enforcement's worst nightmare would be to imagine an individual using a 3-D printer to print a stockpile of firearms that goes unlicensed and unnoticed" (51).

4.5. Long-Term Developments

Organ printing has the potential to revolutionize quality of life for significant numbers of people (see, for example, Reference 52). A community of AM researchers who deal with depositing living matter has arisen. At one point many years ago, success was measured in terms of whether cells could be deposited without dying. This is generally no longer the case. A major issue in the AM community today with respect to organ printing is vascularization, the construction of a network of veins and arteries for blood flow. There have been advances in bone tissue scaffolding and avascular tissue, including cartilage, but the long-term impact will be in the area of organs.

A second area with long-term impact is high-speed, volume-based AM. This will substantially affect build rates. Today's technologies are based mostly on point-by-point deposition of material. Some processes, particularly those involving mask generation or digital micromirror technology, can print on an areal basis. It is conceivable but not yet realized to print on a volume basis. Here a volume space would be defined, and a part would be simultaneously printed at all points/voxels within that volume. The potential would then exist to create a part in a matter of seconds rather than hours or days.

5. SUMMARY AND CONCLUSIONS

Three prehistorical threads of AM include photosculpture, topography, and material deposition, which date back to the 1860s. Precursor AM technologies are defined to be those techniques invented in the 1950s to 1980s, none of which were commercialized and all of which predated the widespread availability of distributed computers with intuitive graphical interfaces. Modern AM, or 3D printing, began with the sale of the first modern machine by 3D Systems in 1987.

According to the ISO/ASTM (1), there are seven broad categories of AM: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization. All are currently commercialized. Current applications for AM are for products that have complex geometries and for which the production run is small. For service parts with demanding properties, the part cost is driven generally by the AM fabricator machine cost coupled with the feedstock cost. Reduction in these costs, improvements in production rates, increased part geometrical complexity, and reduced feedstock scrap rate contribute to increasing the break-even production number to the point that AM competes equally on a cost basis with a traditional manufacturing process.

The AM field has experienced an annual growth rate of ~30% for the period 2010–2015. Several factors have contributed to this remarkable growth rate, including the expiration of founding patents, selection of AM as the theme for the first US MII, increased public awareness, and the development of affordable 3D imaging software. Sectors that have adopted AM include the automotive, aerospace, medical (implants and prosthetics), tooling, art, jewelry, museum display and architecture, and game avatar sectors.

It is proposed that the divergence of high-end and low-end fabricators over the last 20 years will reverse itself, largely due to the decreasing cost of high-end fabricators and improvements in the quality of parts produced on low-end fabricators. AM equipment manufacture and sales have been embraced by a large, multinational equipment company that will spur social adoption of the technologies. AM is an enabling technology for topology optimization that will result in computer-designed part geometries with improved performance. The legal community is starting to specialize in issues specific to AM. Areas of focus include copyright and patent infringement, product liability, and controls on weapon production in light of governmental responsibilities and guaranteed freedoms. Long-term developments in AM that will be transformational are organ printing and volume printing.

This is an exciting time for AM. The technologies are integrating into the public sector on an international basis. Research and development are increasing at a rapid pace. Product commercialization is also growing and diversifying rapidly. Distributed manufacturing has the potential to have an impact comparable to that of distributed computing, which began more than 40 years ago and was an enabling technology for distributed manufacturing. Increased visibility and attention placed on AM will spur and accelerate advancement on both applied and research planes. The remaining challenges have been systematized and defined in a number of research roadmapping studies starting with the 2009 *Roadmap for Additive Manufacturing* (53). The placement of AM technologies within conventional manufacturing is evolving. Currently, economic considerations place AM in applications of short-run, complex geometric parts. Future reductions in the cost of AM equipment and feedstock coupled with increased processing speed will expand the application space for AM.

DISCLOSURE STATEMENT

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LITERATURE CITED

1. ASTM. 2015. *Standard terminology for additive manufacturing—general principles. Part 1: Terminology*. ISO/ASTM Stand. 52792, ASTM
2. Sachs EM, Haggerty JS, Cima MJ, Williams PA. 1993. *Three-dimensional printing techniques*. US Patent 5,204,055
3. Wohlers TW, ed. 2015. *Wohlers Report 2015*. Fort Collins, CO: Wohlers Assoc.
4. Gordon R, Harrop J. 2014. *3D Printing Materials 2015–2025: Status, Opportunities, Market Forecasts*. Cambridge, UK: IDTechEx
5. Malone E, Lipson H. 2006. Fab@Home: the personal desktop fabricator kit. In *Proceedings of the International Solid Freeform Fabrication Symposium, 17th*, pp. 668–81. Austin: Univ. Tex.
6. Beaman J, Bourell D, Wallace D. 2014. Special Issue: Additive Manufacturing (AM) and 3D Printing. *J. Manuf. Sci. Eng.* 136(6):1
7. White House. 2012. *President Obama to announce new efforts to support manufacturing innovation, encourage insourcing*. News Release, Off. Press Secr., White House, Mar. 9. **https://www.whitehouse.gov/the-press-office/2012/03/09/president-obama-announce-new-efforts-support-manufacturing-innovation-en**
8. White House. 2013. *Remarks by the President in the State of the Union Address*. Off. Press Secr., White House, Feb. 12. **https://www.whitehouse.gov/the-press-office/2013/02/12/remarks-president-state-union-address**
9. White House. 2014. *President Barack Obama's State of the Union Address*. Off. Press Secr., White House, Jan. 28. **https://www.whitehouse.gov/the-press-office/2014/01/28/president-barack-obamas-state-union-address**
10. Ashby MF. 2011. *Materials Selection in Mechanical Design*. Boston: Elsevier. 4th ed.
11. Ashley S. 1991. Rapid prototyping systems. *Mech. Eng.* 113(4):34
12. Denton KR, Jacobs PE. 1994. QuickCast^{TM} & rapid tooling: a case history at Ford Motor Company. In *Proceedings of the International Solid Freeform Fabrication Symposium, 5th*, pp. 154–74. Austin: Univ. Tex.
13. OICA. 2015. *Production statistics*. **http://www.oica.net/category/production-statistics/**
14. Pinter D. 2015. *Bentley unites handcraft with 3D printing*. **http://www.psfk.com/2015/03/bentley-concept-car-exp-10-speed-6–2015-geneva-auto-show.html**
15. Dickey MR. 2015. Hope you trust 3D printers—Boeing uses them to 'print' parts for its planes. *Business Insider*, June 21. **http://www.businessinsider.com/boeing-uses-3d-printers-for-airplane-parts-2013-6**
16. Jeantette FP, Keicher DM, Romero JA, Schanwald LP. 2000. *Method and system for producing complex-shape objects*. US Patent 6,046,426
17. Weiss L, Prinz FR, Gursoz L. 1992. *Method and apparatus for fabrication of three-dimensional articles by thermal spray deposition*. US Patent 5,126,529
18. Periard D, Schaal N, Schaal M, Malone E, Lipson H. 2007. Printing food. In *Proceedings of the International Solid Freeform Fabrication Symposium, 18th*, pp. 564–74. Austin: Univ. Tex.
19. Landers R, Mülhaupt R. 2000. Desktop manufacturing of complex objects, prototypes and biomedical scaffolds by means of computer-assisted design combined with computer-guided 3D plotting of polymers and reactive oligomers. *Macromol. Mater. Eng.* 282:17–21
20. Gothait H. 2001. *Apparatus and method for three dimensional model printing*. US Patent 6,259,962
21. Deckard C. 1989. *Method and apparatus for producing parts by selective sintering*. US Patent 4,863,538
22. Hull C. 1986. *Apparatus for production of three-dimensional objects by stereolithography*. US Patent 4,575,330
23. Munz OJ. 1956. *Photo-glyph recording*. US Patent 2,775,758
24. Kodama H. 1981. Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer. *Rev. Sci. Instrum.* 52:1770–73
25. Herbert AJ. 1982. Solid object generation. *J. Appl. Photo Eng.* 8(4):185–88
26. Beaman JJ, Barlow JW, Bourell DL, Crawford RH, Marcus HL, McAlea KP. 1997. *Solid Freeform Fabrication: A New Direction in Manufacturing*. Boston: Kluwer
27. Wohlers T, Gornet T. 2014. History of additive manufacturing. In *Wohlers Report 2014*, ed. TW Wohlers. pp. 14–17. Fort Collins, CO: Wohlers Assoc. **http://wohlersassociates.com/history2014.pdf**

28. Bogart M. 1979. In art the end don't always justify means. *Smithsonian* 9:104–10
29. Baese C. 1904. *Photographic process for the reproduction of plastic parts*. US Patent 774,549
30. Morioka I. 1935. *Process for manufacturing a relief by the aid of photography*. US Patent 2,015,457
31. Blanther JE. 1892. *Manufacture of contour relief maps*. US Patent 473,901
32. Perera BV. 1940. *Process of making relief maps*. US Patent 2,189,592
33. Zang EE. 1940. *Vitavue relief model technique*. US Patent 3,137,080
34. Gaskin TA. 1973. *Earth science teaching device*. US Patent 3,751,827
35. Matsubara K. 1974. *Molding method of casting using photocurable substance*. Jpn. Kokai Patent Appl. Sho 51[1976]-10813
36. DiMatteo PL. 1976. *Method of generating and constructing three-dimensional bodies*. US Patent 3,932,923
37. Nakagawa T. 1979. Blanking tool by stacked bainite steel plates. *Press Tech.* 1979:93–101
38. Kuneida M, Nakagawa T. 1984. Development of laminated drawing dies by laser cutting. *Bull. JSPE* 18(4):353–54
39. Nakagawa T, Kunieda M, Liu SD. 1985. Laser cut sheet laminated forming dies by diffusion bonding. In *Proceedings of the 25th International Machine Tool Design and Research Conference*, pp. 24–25. Birmingham: Univ. Birmingham
40. Baker R. 1925. *Method of making decorative articles*. US Patent 1,533,300
41. Garver FW. 1961. *Method of producing metal rollers*. US Patent 3,007,231
42. White WD Jr. 1964. *Pressure roller and method of manufacture*. US Patent 3,156,968
43. Brandi HT, Luckow H. 1976. *Method of making large structural one-piece parts of metal, particularly one-piece shafts*. US Patent 3,985,995
44. Gale PL, Fair JE. 1978. *Method of making aluminum piston with reinforced piston ring groove*. US Patent 4,125,926
45. Brown CO, Beinan EM, Kear BH. 1982. *Method for fabricating articles by sequential layer deposition*. US Patent 4,323,756
46. Ciraud PA. 1972. *Verfahren und Vorrichtung zur Herstellung beliebiger Gegenstaende aus beliebigem schmelzbarem Material* [Process and device for the manufacture of any objects desired from any meltable material]. Ger. Patent Appl. DE 22 63 777 A1
47. Swainson WK. 1977. *Method, medium and apparatus for producing three-dimensional figure product*. US Patent 4,041,476
48. Housholder R. 1981. *Molding process*. US Patent 4,247,508
49. NCMS. 1998. *The road to manufacturing: 1998 industrial roadmap for the rapid prototyping industry*. Rep. 0199RE98, NCMS
50. Leitão P. 2009. Agent-based distributed manufacturing control: a state-of-the-art survey. *Eng. Appl. Artif. Intell.* 22(7):979–91
51. Johnson JJ. 2013. Print, lock, and load: 3-D printers, creation of guns, and the potential threat to Fourth Amendment rights. *J. Law Technol. Policy* 2013(2):338–60
52. Murphy SV, Atala A. 2014. 3D bioprinting of tissues and organs. *Nat. Biotechnol.* 32:773–85
53. Bourell DL, Leu MC, Rosen DW, ed. 2009. *Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing*. Austin: Univ. Tex.