A Brief History of Additive Manufacturing and the 2009 Roadmap for Additive Manufacturing: Looking Back and Looking Ahead

David L. Bourell[a], Joseph J. Beaman, Jr.[a], Ming C. Leu[b] and David W. Rosen[c]
[a]Laboratory for Freeform Fabrication, Mechanical Engineering Department, The University of Texas at Austin
[b]Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology
[c]George W. Woodruff School of Mechanical Engineering , Georgia Institute of Technology
dbourell@mail.utexas.edu

Abstract - **Additive Manufacturing (AM) has roots in topography and photosculpture which date back almost 150 years. Both of these early technologies might be categorized as manual "cut and stack" approaches to building a freeformed object in a layerwise fashion. The first successful AM process was effectively a powder deposition method with an energy beam proposed by Ciraud in 1972. Other historical developments in AM will be described in the presentation. Transitioning from the oldest developments in AM to the most recent, earlier this year sixty-five experts in AM gathered in the Washington DC area to develop a research roadmap for AM. The results of that effort are described.**

Keywords –**History, Roadmap, Workshop**

I. INTRODUCTION

Freeform Fabrication (FF) is an emerging collection of technologies also known as rapid prototyping, rapid manufacturing and solid freeform fabrication, and more broadly as a subset of additive manufacturing (AM). In 2008 worldwide AM products and services totaled almost $1.2 billion. The value of parts and services has increased by about 10% annually for the last five years (1).

Freeform fabrication technologies serve a well defined market niche. Applications share the common characteristics of production of parts with complex geometry in relatively small production runs. Historically, applications were limited to production of prototypes and casting inserts, since part mechanical properties and surface finish were inadequate for actual structural applications. More recently, coupled with post processing, FF has been used to produce a variety of production tooling, short-run structural parts, customized bio-engineered parts, mass-customized parts, architectural designs, archaeological replicas and artwork (2).

The purpose of this paper is to describe the historical context of AM technology and to report on one of the most recent developments in the field, a US national roadmap study to define research needs and possibilities for AM in the next 10-15 years.

II. ADDITIVE MANUFACTURING PREHISTORY

An essential element of Additive Manufacturing is layerwise creation of a part. From a review of the US patent literature, two early roots were identified: topography and photosculpture. Figure 1 displays the early chronology of AM. This chronology should not be considered complete; it indicates some (but not all) of the major time events in this field up to about 2002.

A. Topography

As early as 1890,Blanther (3) suggested a layered method for making a mold for topographical relief maps. The method consisted of impressing topographical contour lines on a series of wax plates and cutting these wax plates on these lines. After stacking and smoothing these wax sections, one obtains both a positive and negative three-dimensional surface that corresponds to the terrain indicated by the contour lines. After suitable backing of these surfaces, a paper map is then pressed between the positive and negative forms to create a raised relief map. This is shown in Figure 2.

In a similar fashion, Perera (4) proposed a method for making a relief map by cutting contour lines on sheets (cardboard) and then stacking and pasting these sheets to form a three-dimensional map. Further refinements of this approach are found in Zang (5) who suggested using transparent plates with topographical detail inscribed on each plate and Gaskin (6) who described a three dimensional geological teaching device. In 1972, Matsubara of Mitsubishi Motors (7) proposed a topographical process that uses photo-hardening materials. In this process, a photopolymer resin

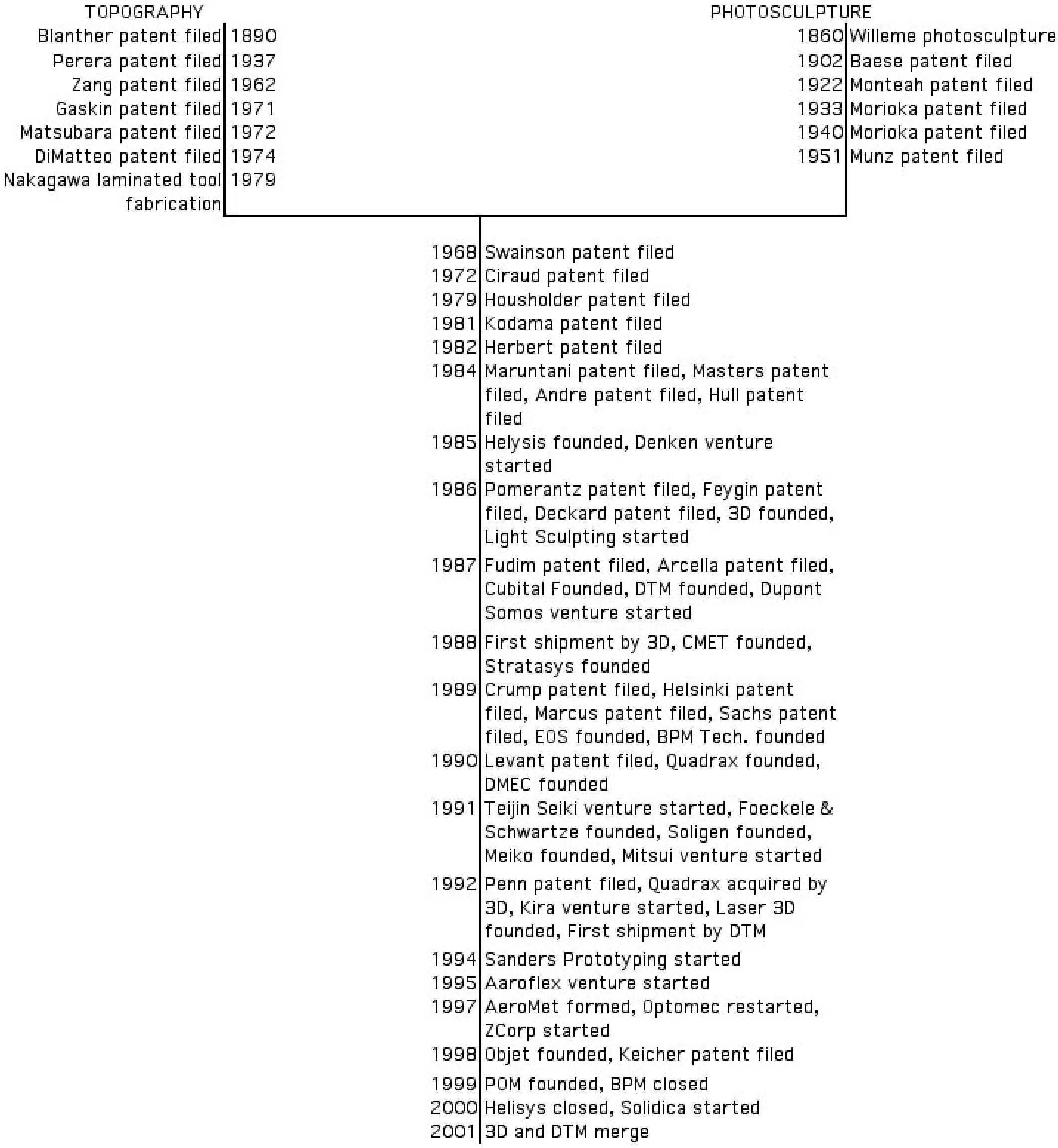


Fig. 1. Early Chronology of Additive Processes

is coated onto refractory particles (e.g., graphite powder or sand). These coated particles are then spread into a layer and heated to form a coherent sheet. Light (e.g., mercury vapor lamp) is then selectively projected or scanned onto this sheet to harden a defined portion of it. The unscanned, unhardened portion is dissolved away by a solvent. The thin layers formed in this way are subsequently stacked together to form a casting mold. In 1974, DiMatteo (8) recognized that these same stacking techniques could be used to produce surfaces that are particularly difficult to fabricate by standard machining operations. In one embodiment, a milling cutter contours metallic sheets, these sheets are then joined in layered fashion by adhesion, bolts, or tapered rods. This process has obvious similarity to the earlier 19th century work.

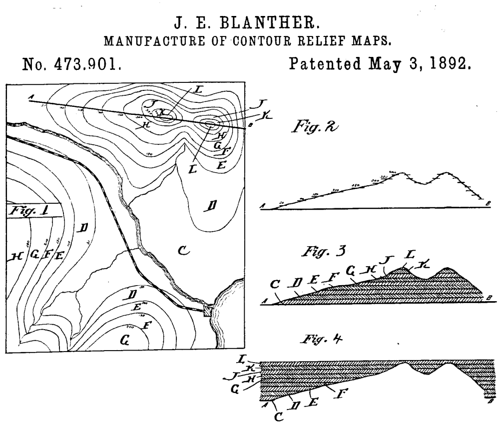


Fig. 2. Blanther patent to fabricate 3-D relief map with layered method

In 1979, Professor Nakagawa of Tokyo University began to use lamination techniques to produce actual tools such as blanking tools (9), press forming tools (10), and injection molding tools (11). A laminated punch tool and the resultant part are shown in Figure 3.

B. Photosculpture

Photosculpture arose in the 19th century as an attempt to create exact three-dimensional replicas of any object, including human forms (12). One, somewhat successful realization of this technology was designed by Frenchman François Willème in 1860. As shown in Figure 4, a subject or object was placed in a circular room and simultaneously photographed by 24 cameras placed equally about the circumference of the room. An artisan then carved a 1/24th cylindrical portion of the figure using a silhouette of each photograph as seen in Figure 5.

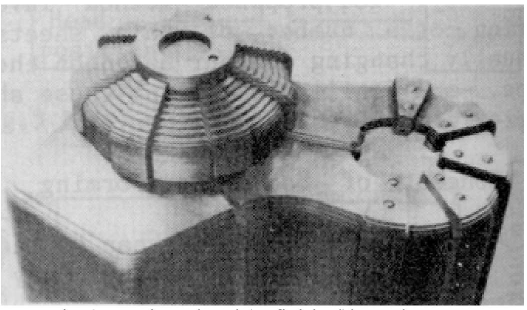


Fig. 3. Laminated tool (unfinished)by Nakagawa

Fig. 4.Photosculpture in Willème's studio

In an attempt to alleviate the labor-intensive carving step of Willème's photosculpture, Baese (13) described a technique using graduated light to expose photosensitive gelatin that expands in proportion to exposure when treated with water. Annular rings of this treated gelatin could then be fixed on a support to make a replica of an object as shown in Figure 6.

Fig. 5. Solid reproduction from Willème's photosculpture

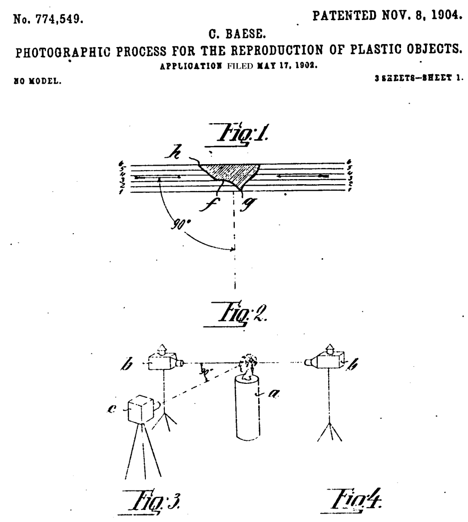


Fig. 6. Baese photosculpture technique

Monteah developed similar techniques (14). In some of the earliest work in Japan, Morioka (15, 16) developed a hybrid process between photosculpture and topography. This method uses structured light (black and white bands of light) to photographically create contour lines of an object. These lines could then be developed into sheets and then cut and stacked or projected onto stock material for carving.

III. DEVELOPMENT OF MODERN AM TECHNIQUES

In 1951, Munz (17) proposed a system that has features of present day stereolithography techniques. He disclosed a system for selectively exposing a transparent photo emulsion in a layerwise fashion where each layer comes from a cross section of a scanned object. Lowering a piston in a cylinder and adding appropriate amounts of photo emulsion and fixing agent create these layers. After exposing and fixing, the resulting solid transparent cylinder contains an image of the object. Subsequently this object can be manually carved or photochemically etched out to create a three-dimensional object. This system is shown in Figure 7.

In 1968, Swainson (18) proposed a process to directly fabricate a plastic pattern by selective, three dimensional polymerization of a photosensitive polymer at the intersection of two laser beams. Parallel work was conducted at Battelle Laboratories (19). The essential features of this process, termed Photochemical Machining, are depicted in Figure 8. The object is formed by either photochemically crosslinking or degrading a polymer by simultaneous exposure to intersecting laser beams. Although laboratory hardware was constructed, a commercially viable process was not achieved.

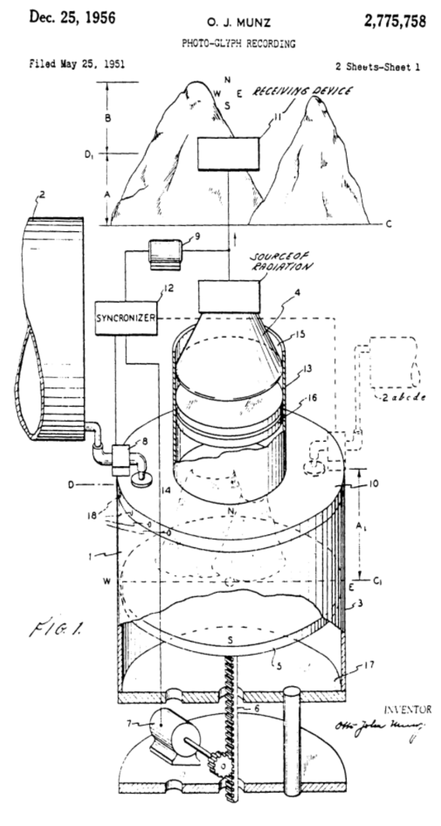


Fig. 7. Photopolymer technique of Munz

Ciraud proposed a powder process that has all the features of modern direct deposition AM techniques in 1971 (20). This disclosure describes a process for the manufacture of objects from a variety of materials that are at least partially able to melt. To produce an object, small particles are applied to a matrix by gravity, magnetostatics, electrostatics, or positioned by a nozzle located near the matrix. A laser, electron beam,or plasma beam then heats the particles locally. As a consequence of this heating, the particles adhere to each other to form a continuous layer. As shown in Figure 9, more than one laser beam can be used to increase the strength of the union between the particles.

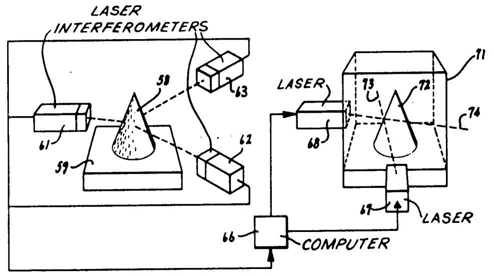


Fig. 8. Photochemical SFF system of Swainson

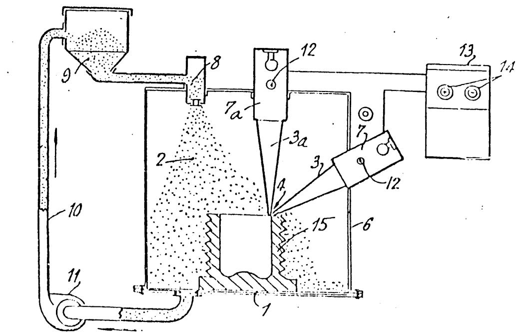


Fig. 9. Powder SFF process of Ciraud

In 1979, Housholder (21) presented the earliest description of a powder laser sintering process in a patent. He discussed sequentially depositing planar layers and solidifying a portion of each layer selectively. The solidification can be achieved by using heat and a selected mask or by using a controlled heat scanning process, Figure 10.

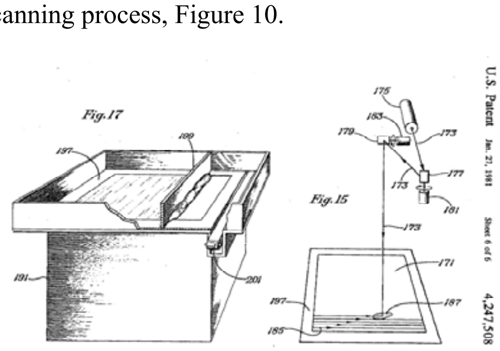


Fig. 10. Powder process of Housholder

Hideo Kodama of Nagoya Municipal Industrial Research Institute was the first to publish an account of a functional photopolymer rapid prototyping system (22). In his method, a solid model is fabricated by building up a part in layers where exposed areas correspond to a cross-section in the model. He studied three different methods for achieving this, Figure 11: (a) Using a mask to control exposure of UV source and immersing the model downward into a liquid photopolymer vat to create new layers; (b) Using a mask as in (a), but the mask and exposure is positioned on the bottom of the vat and the model is drawn upward to create a new layer; (c) Immersing the model, as in (a), but using an x-y plotter and an optical fiber to expose the new layer.

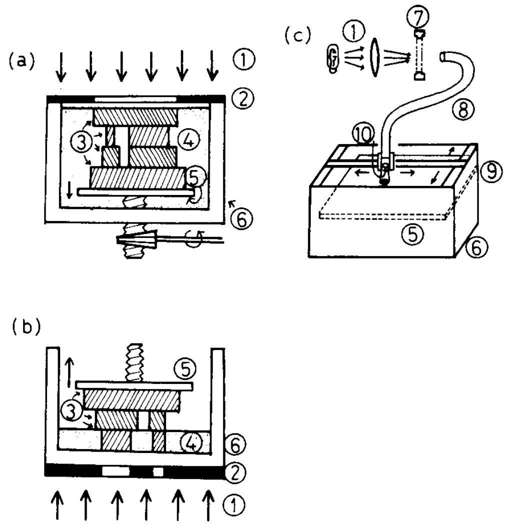


Fig. 11. Stereolithography systems of Kodama

Herbert conducted a second, parallel but independent effort at 3M (23). Herbert describes a system that directs a UV laser beam to a photopolymer layer by means of a mirror system on an x-y plotter, Figure 12. In Herbert's experimental technique, a computer was used to command a laser beam across a layer, the photopolymer vessel was then lowered (1 mm), and additional liquid photopolymer was then added to create a new layer.

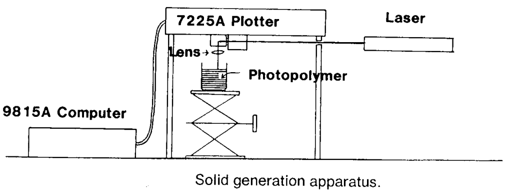
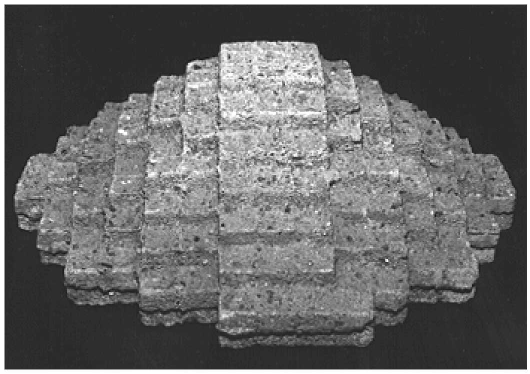
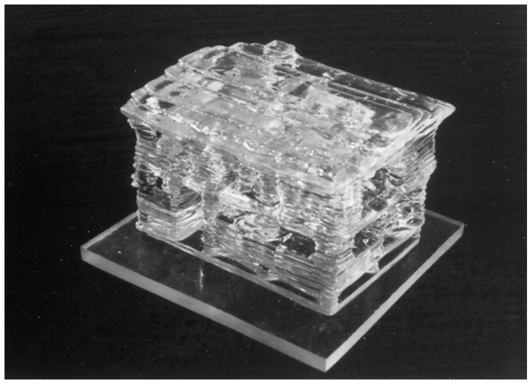


Fig. 12. Stereolithography system of Herbert

Although very intricate parts can be produced by AM equipment today, the first parts out of these types of systems required a good deal of faith that improvements would occur. Shown in Figure 13 are three early parts from different systems. The Housholder part was made from an embodiment that includes a grid for separating mold material (concrete and water) from casting material (dry concrete). The Herbert part was created in August 1979. Creation dates for the Kodama and Housholder parts are not known.



Housholder



Kodama

Herbert

Fig. 13. Early parts by Housholder, Kodama, and Herbert

IV. 2009 ROADMAP FOR ADDITIVE MANUFACTURING

In the late 1980s and early 1990s a plethora of AM processes appeared. Over the ensuing twenty years, the research community has for the most part applied these processes and process variations in novel ways to attack a wide variety of research problems in a diverse number of technical areas. The impact of additive fabrication continues to grow, in terms of both commercial and scholarly activities. Two WTEC studies were performed on AM in Europe and Japan in 1996. An NCMS roadmap study on AM was completed two years later, which emphasized industrial applications of the technology. In 2003, another WTEC study was performed to assess the level of activity in Europe in additive/subtractive technologies. The reports from these events provided key data points and served as the basis for a new research roadmap study in 2009.

The objective of the workshop “Roadmap for Additive Manufacturing (RAM) Workshop: Identifying the Future of Freeform Processing” was to develop and articulate a roadmap for research in the area of additive manufacturing for the next 10-12 years. The workshop was intended to: accelerate the integration of AM technologies into the marketplace; identify potential, fruitful research areas for additive manufacturing for the next 5-10 years; network leading experts in the field from industry, academia and government with synergistic results; lay out a thoughtful and systematic plan for additive manufacturing research for the near and medium term.

The workshop was attended by 65 key people in the field of additive manufacturing from academia, industry and government. It included four keynote presentations with follow-on discussions to broadly identify trends, barriers, opportunities, milestones, and vocabulary of additive manufacturing. The workshop continued with seven breakout sessions to simultaneously develop research needs and issues on: Industry Targets, Technological Goals & Barriers, Design and Analysis, Processes & Machines, Materials & Processing, Bio-Additive Manufacturing, and Energy & Sustainability. The workshop report [24] summarizes the discussion results, with one chapter for each breakout topic and the last chapter providing recommendations for future research.

The main recommendations from the RAM workshop may be summarized.

Design

- Create conceptual design methods to aid designers in defining and exploring design spaces enabled by AM.
- Produce a new foundation for computer-aided design systems to overcome the limitations of existing solid modeling in representing complex geometries and multiple materials.
- Provide a multiscale modeling and inverse design methodology to assist in navigating complex process-structure-property relationships.
- Create methods to model and design with variability: shape, properties, process, etc.

Process Modeling and Control

- Develop predictive process-structure-property relationships integrated with CAD/E/M tools.
- Create closed-loop and adaptive control systems with feedforward and feedback capabilities.
- Produce new sensors that can operate in build chamber environments and sensor fusion methods.

Materials, Processes and Machines

- Develop a better understanding of the basic physics of AM processes to capture the complexity in the multiple interacting physical phenomena.
- Create scalable, fast material processing methods using line or area to greatly increase machine throughput.
- Produce open-architecture controllers and reconfigurable machine modules.
- Exploit unique AM characteristics to produce epitaxial metallic structures, fabricate functionally gradient materials and multiple materials, and embed components during fabrication processes.
- Screen methodologies to answer the question as to why some materials are processable by AM and some are not; Tools for AM fabrication of structures and devices atom by atom and design for nanomanufacturing.
- Develop and identify of sustainable (green) materials including recyclable, reusable, and biodegradable materials.

Biomedical Applications

- Design and model methods for customized implants and medical devices
- Develop viable Bio-AM (BAM) processes for fabrication of “smart scaffolds” and construction of 3D biological and tissue models using living biologics
- Create computer-aided BAM including modeling, analysis and simulation of cell responses and cell-tissue growth behavior.

Energy and Sustainability Applications

- Design energy system components to take advantage of AM capabilities

- Pursue Maintenance, Repair, and Overhaul (MRO) in the aerospace industry as a potential AM application
- Develop equitable indicators for measuring sustainability in AM processes and products and identify sustainable engineering materials for AM processes.

Education

- Develop university courses, education materials, and curricula at both the undergraduate and graduate levels, as well as at the technical college level
- Develop training programs for industry practitioners with certifications given by professional societies or organizations.

Development and Community

- Reduce machine, material and servicing costs to ensure the affordability of AM in relation to conventional manufacturing
- Develop and adopt internationally recognized standards (such as the recently initiated ASTM Committee F42) useful to product, process and material certification.

National Testbed Center

- Establish a national testbed center having one or more sites with distributed AM machines and/or expert users to leverage equipment and human resources in future research and to exemplify the cyber-enabled manufacturing research concept.

V. CONCLUSIONS

The roots of modern additive manufacturing (AM) trace back about 40 years, although preceding topographic and photosculpture methods share much in common with AM and are over 100 years old. Appreciation of the prehistory of AM provides a rich backdrop for current and future developments. One such articulation of the future was a research roadmap exercise organized by the authors [24]. In addition to technical targets, educational needs and a national testbed center were highlighted.

REFERENCES

[1] T. Wohlers, "Wohler's Report 2009", Wohlers Associates, Inc., (OakRidge Business Park, 1511 River Oak Drive, Fort Collins, Colorado 80525, 2009).

[2] Proceedings of the Solid Freeform Fabrication Symposium, (Mechanical Engineering Department, The University of Texas, Austin, Texas 78712, 1990-2009).

[3] J.E. Blanther, "Manufacture of Contour Relief Maps ", US Patent #473,901, 1892.

[4] B.V. Perera, "Process of Making Relief Maps ", US Patent #2,189,592, 1940.

[5] E.E. Zang, "Vitavue Relief Model Technique", US Patent #3,137,080, 1964.

[6] T.A. Gaskin, "Earth Science Teaching Device ",US Patent #3,751,827, 1973.

[7] K. Matsubara, "Molding Method of Casting Using Photocurable Substance ", Japanese Kokai Patent Application, Sho 51 [1976]-10813, 1974.

[8] P.L. DiMatteo, "Method of Generating and Constructing Three-Dimensional Bodies",US Patent #3,932,923, 1976.

[9] T. Nakagawa, et al, "Blanking Tool by Stacked Bainite Steel Plates ", *Press Technique*, 1979, pp. 93-101.

[10] M.a Kunieda, T. Nakagawa,"Development of Laminated Drawing Dies by Laser Cutting " ,*Bull of JSPE* ,1984, pp.353-54.

[11] T. Nakagawa, *et al*, "Laser Cut Sheet Laminated Forming Dies by Diffusion Bonding", *Proc 25th MTDR Conf* ,1985, pp.505-510.

[12] M. Bogart, "In Art the End Don't Always Justify Means ", *Smithsonian*, 1979, pp.104-110.

[13] C. Baese, "Photographic Process for the Reproduction of Plastic Objects", US Patent #774,549, 1904.

[14] F.H. Monteah, "Photochemical Process for Producing BAS Reliefs", US Patent #1,516,199, 1924.

[15] I. Morioka, "Process for Manufacturing a Relief by the Aid of Photography", US Patent #2,015,457, 1935.

[16] I. Morioka, "Process for Plastically Reproducing Objects", US Patent #2,350,796, 1944.

[17] O.J. Munz, "Photo-Glyph Recording", US Patent #2,775,758, 1956.

[18] W.K. Swainson, "Method,Medium and Apparatus for Producing Three-Dimensional Figure Product", US Patent #4,041,476, 1977.

[19] R.E. Schwerzel, *et al*, "Three-Dimensional Photochemical Machining with Lasers", *Appl of Lasers to Ind Chem,* SPIE, 1984, pp.90-97.

[20] P.A. Ciraud, "Process and Device for the Manufacture of any Objects Desired from any Meltable Material", FRG Disclosure Publication 2263777, 1972.

[21] R.F. Housholder, "Molding Process", US Patent #4,247,508, 1981.

[22] H. Kodama, "Automatic Method for Fabricating a Three-Dimensional Plastic Model with Photo Hardening Polymer", *Rev Sci Instrum*, 1981, pp.1770-73.

[23] A.J. Herbert, "Solid Object Generation", *Jour Appl Photo Eng*, 8#4, August 1982, pp. 185-88.

[24] "Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing", D.L. Bourell, M.C. Leu, D.W. Rosen, eds., Univ. of Texas, 2009, 92 pages. Available for free on-line download at http://wohlersassociates.com/roadmap2009.pdf.