techsolutions 12

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An Overview of Additive Manufacturing, Part I

This article is the first part in a two-part series on additive manufacturing. It presents a brief introduction to several additive manufacturing processes, such as stereolithography, fused deposition modeling, and laminated object manufacturing. The second installment in this two-part series will be published in an upcoming issue of TechSolutions. - Editor

INTRODUCTION

In the 21st century, consumer markets demand less expensive products that can be manufactured faster than in previous generations of a product. Therefore, advances in manufacturing concepts and technologies must be achieved to reduce new product development times, manufacturing cycle times, and production costs. The cost of procuring and setting up traditional production machinery (e.g., mills, lathes, grinders, etc.) can increase the unit cost of a product, and the impact is exaggerated if only a small number of units are being produced. Moreover, traditional production processes are *subtractive*, which means that the finished product is machined out of a larger block of material, and thus generates material waste. As the 21st century loomed on the horizon, manufacturers and product designers researched the ability of processes like additive manufacturing (AM) to reduce machine cycle time and waste. Additive manufacturing refers to a process that builds up a component in layers.[1] Additive manufacturing is known by several different names, the most common of which are rapid prototyping, rapid tooling, rapid manufacturing, direct digital manufacturing, and solid free-form fabrication. This article provides an overview of AM processes and presents current and emerging applications of AM technology for commercial and defense industries.

HISTORY OF ADDITIVE MANUFACTURING

Originally developed as a quick and cost-effective method to produce mock-up or prototype components, additive manufacturing was first known as rapid prototyping in the mid-1980's. Additive manufacturing processes have since helped revolutionize the manufacturing industry and it has spun off various production technologies and tooling methods that are used throughout commercial industry and the Department of Defense (DoD).

In 1986, Charles Hull applied for and received a patent for an "Apparatus for Production of Three-Dimensional Objects by Stereolithography" (US Patent 4,575,330).[5] Carl Deckard, a researcher at the University of Texas, received a grant from the National Science Foundation in 1987 to develop a selective laser sintering (SLS) process.[6] Three-dimensional (3D) printing technologies developed in the 1980's helped jump start a cottage industry in the 21st century to produce customized components to fill orders via the Internet. In the 1990's, the additive manufacturing industry continued to grow as technology improved and new concepts were developed.

With the advancement of computer-aided design (CAD) modeling technology in the 21st century, AM processes are more capable of fabricating complex components. As a result, processes, such as direct digital manufacturing and mass customization, have become more practical. These advancements, in combination with material improvements, have helped AM processes evolve from a method for fabricating design prototypes to a method for making fully functional prototypes, tooling, molds, and low volume production runs.

Parts fabricated via AM are traditionally produced using either photopolymeric or metallic materials. Photopolymers are liquid, solid, or powder-based resins that are cured and shaped using ultraviolet (UV) light sources. Metallic components, which are usually powder-based, range from low alloy steel to aluminum, titanium, copper, and tungsten. A more detailed list of processes and materials is provided in Table 1.

LIQUID-BASED ADDITIVE MANUFACTURING

In liquid-based AM processes a photo-sensitive polymer resin is cured or solidified using an ultraviolet (UV) light source.[10] Such processes are used to manufacture fully functional prototypes, mold patterns for metal casting, and low volume production of certain plastic components.

Additive Manufacturing Definitions [1-4]

Term	Definition
Rapid prototyping	The use of a digital model, such as CAD, to construct a *prototype* by depositing a material onto a substrate
Direct digital manufacturing	Transformation of a digital representation or design of a part to a finished product using additive manufacturing
Rapid manufacturing	Use of additive manufacturing processes to make fully-functioning products
Rapid tooling	The use of additive manufacturing processes to create a mold cavity or directly fabricate a limited volume of tools

Table 1. **Examples of additive manufacturing processes and materials. [7-9]**

Process	Materials
Stereolithography	Acrylic photopolymer
	Epoxy photopolymer
	Vinyl ether photopolymer
Fused deposition modeling	Acrylonitrile butadiene styrene (ABS)
	Polycarbonate
	Polyester
	Polyphenylsulfone
Laminated object manufacturing	Aluminum
	Paper
	Poly vinyl carbonate (PVC)
	Acrylonitrile butadiene styrene (ABS)
	Polycarbonate
	Polyester
	Titanium nitrite
	Ceramics
	Miscellaneous metals
Electron beam melting*	Superalloys
	Stainless steels
	Tool steels
	Aluminum
	Titanium
	Copper
Laser Engineered Net Shaping™*	316, 304, 17-4 stainless steels
	Nickel-based superalloys
	Tungsten
	Copper
	Aluminum
	M300 steel
	H13 tool steel
	Titanium
	Low alloy steel
	Nickel aluminides
Selective laser sintering*	Polystyrene
	Sand
	Polycarbonate
	Polyamide
	Glass filled polyamide
	Tungsten
	Copper
	Aluminum
	Low alloy steel
Inkjet/3D Printing*	316L stainless steel + bronze
	420 stainless steel + bronze
	Wax
	Starch
	Plaster
	Molding Sand

** These processes will be highlighted in Part II of this article.*

Stereolithography

Stereolithography (SL) is used to make solid objects by successively printing thin layers of a photo-curable material.[5] To build each layer, a pattern is drawn and cured by an ultraviolet laser whose path is derived from a CAD drawing of the part. Once the layer is cured, a new layer of photopolyermic resin is distributed on top of the previous layer, and the laser curing process continues until the part is fully formed (see Figure 1).[11] Stereolithography was also the first AM technology developed for use in commercial applications. Originally used to produce parts for physical mock-ups in the design phase, SL is now used for everything from short production runs to shell molds for investment casting. The high dimensional accuracy of SL produces a higher quality mold than traditional molding processes. This accuracy helps ensure the production of a more precise mold without incurring long lead times that have plagued the investment casting process in the past.[13]

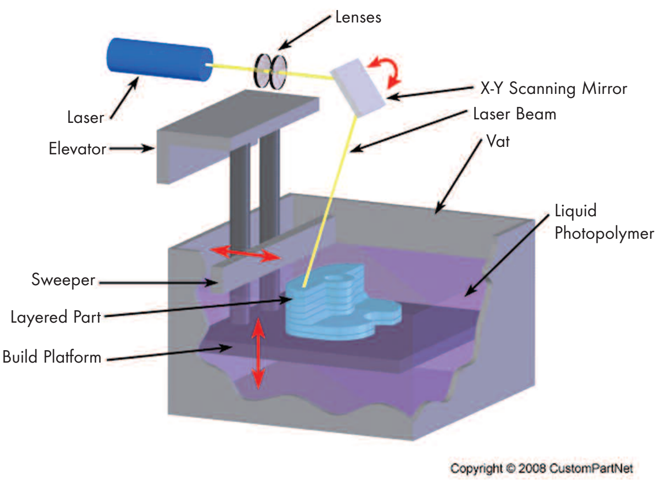

Figure 1. **An illustration of the stereolithography process. (Image courtesy of CustomPartNet, Copyright © 2008)[12]**

Sterolithography has made its way into the medical field in recent years. Currently, it can be linked with image scanning systems like computed tomography (CT) scanners and magnetic resonance imaging (MRI) machines to produce accurate re-creations of anatomical components (e.g., bones, cartilage, etc.). These re-creations have been useful in pre-surgery planning, during which the surgical team can now more precisely identify obstacles and plan the surgical steps prior to surgery.[14] Other applications are listed in Table 2.

Table 2. **Industrial applications of stereolithography. [14-16]**

Industry	Application
Firearms	Functional model for form and fit analysis
Medical	Development of replica body parts for pre-surgical planning
	Fabrication of cranial implant
	Surgical aid for dental implant surgery
Furniture	Functional model for form, fit and function design
Power generation	Functional model for verification of redesign
Architecture	Three-dimensional representation of structural plans

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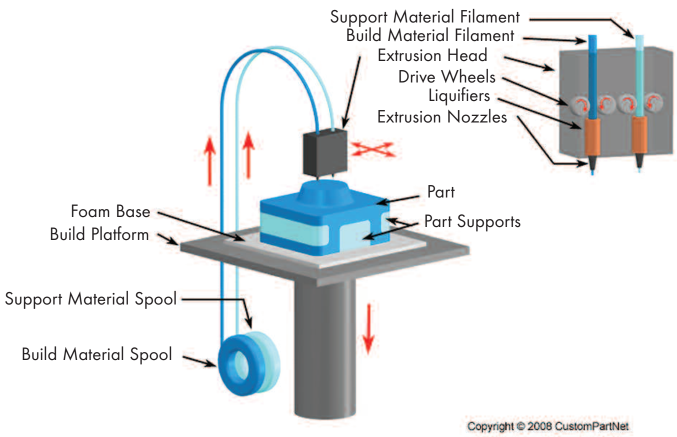

Figure 2. **An illustration of the fused deposition modeling process. (Image courtesy of CustomPartNet, Copyright © 2008)[18]**

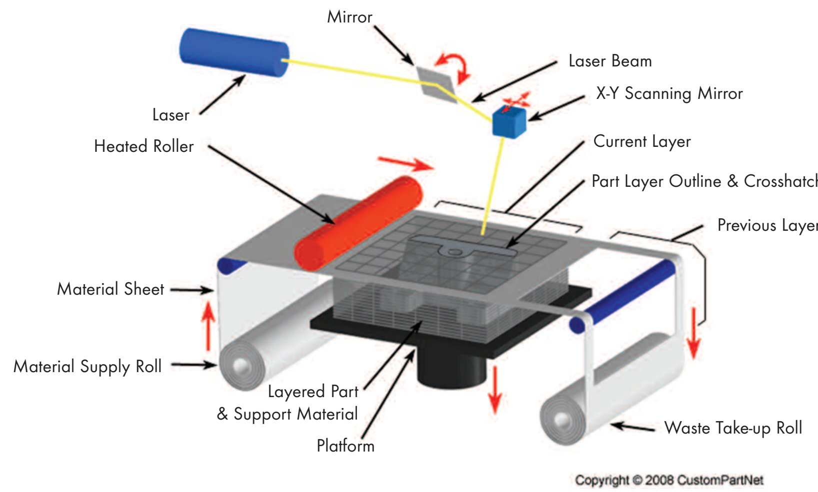

Figure 3. **An illustration of the laminated object manufacturing process. (Image courtesy of CustomPartNet, Copyright © 2008)[22]**

SOLID-BASED ADDITIVE MANUFACTURING

Solid-based AM are processes, such as fused deposition modeling (FDM) and laminated object manufacturing, that shape solid or semi-solid state materials (usually through an extrusion) in a high temperature environment. These processes are used primarily to fabricate fully-functional prototypes and mold cavities for investment casting parts.

Fused Deposition Modeling

Invented in 1989, fused deposition modeling is a process that produces thermoplastic and wax components through the deposition of molten material on a substrate.[17] To produce parts, the material (usually in wire form) is heated to just below melting temperature, extruded through a nozzle, and deposited in a pattern developed from a CAD drawing (see Figure 2). The individual layers, which traditionally range from 0.002 to 0.030 inches, are adhered to the previous layer through heat conduction and cooling.[19] Parts made with FDM require the use of a base, which is a brittle material that can be easily separated from the finished product without tools or damaging the part.[17] A base is used because the material does not cool fast enough to maintain its rigidity and dimensionality during deposition.

While the most common application of FDM is for the fabrication of geometric and functional prototypes, this process has gained popularity in the casting community. Compared to injection molding, thermoplastic and wax mold cavities can be produced with greater dimensional accuracy because FDM is not as sensitive to thermal expansion. In addition, a variety of plastic materials and colors can be used during the production of a single product. FDM has been used in the automotive industry for everything from mock-up parts for racing teams to fully-functional motorcycle components.[20] A sample list of industries that use FDM is shown in Table 3.

Table 3. **Industrial application of fused deposition modeling.[21]**

Industry	Application
Automotive and racing	Prototype motorcycle engine
	Design prototypes for race car mock-up
Banking	Production of assembly aid fixturing for automated teller machinery (ATM)
Computer manufacturing	Fully functional prototypes for computer accessories
Fire and rescue	Prototype hand-held thermal-imaging system for fit analysis
Aviation	Prototype wiring conduits for Osprey helicopter
Home and lawn care	Prototype sprinklers for functional testing
	Production of assembly fixtures for vacuum cleaners
Marine	Prototype parts for functional testing
	Production of outer shell for whale tracking device
Medical	Prototype medical tool for functional testing

Laminated Object Manufacturing

Laminated object manufacturing (LOM) or laminated layer manufacturing is a process that utilizes a polyethylene coating to build 3D shapes. Developed in 1988, LOM uses rolls of a thin material (usually paper) to build up layers in a cross-hatched pattern (see Figure 3).[19] Each layer is heated by a roller, which activates the adhesive backing and enables it to stick to the layer below. After each layer is in place, the outline of a cross-sectional pattern is cut using a carbon dioxide (CO_2) laser. As the part is constructed, a border and cubes are cut into the pattern with the laser to secure the laminated layers during the production process.[23] Once the part has been built up, the cubes are removed in a secondary operation. Because of the relatively simple production process, any material that can be made into a thin foil material and cut with a CO_2 laser can be used with LOM. However, paper, plastic and ceramic materials are the most widely used (refer to Table 1). The LOM process has gained popularity because it can produce parts without subjecting them to the internal stresses incurred in other processes. Thus, LOM produced parts do not suffer distortion, shrinkage, or material deformation because there is little internal

Table 4. Industrial applications of laminated object manufacturing. [8]

Industry	Application
Plastic component fabrication	Rotation molding pattern Resin transfer molding pattern
Metallic/ceramic component fabrication	Sand casting pattern Investment casting pattern
Civil engineering	Physical models Sculpture re-creation
Medical	Artificial limb patterns Bone structures for surgical preparation

tension during processing.[8] In addition, the LOM process can produce relatively large components (up to 20x30x20 inches).[23]

LOM is primarily used in the casting and forging industries and is capable of producing large and complex mold patterns. This process is particularly useful in the development of molds and dies for rapid tooling. In addition, LOM materials are traditionally non-toxic and easily disposable, which makes them ideal for environmentally-friendly mold designs. A list of industrial applications that utilize LOM is shown in Table 4.

SUMMARY

This article, which is part one of a two-part series on additive manufacturing, provided an introduction to several liquid- and solid-based additive manufacturing technologies. The second article in this series will present powder-based additive manufacturing processes, including electron beam melting, Laser Engineered Net Shaping™, selective laser sintering, and three dimensional printing. In addition, the article will briefly describe the benefits of additive manufacturing for Department of Defense applications.

Further information on applications, machinery suppliers, technologies, and countries that employ additive manufacturing can be found in the "Rapid Prototyping: State of the Art Review" published in 2003. This report can be downloaded from the following url: http://ammtiac.alionscience.com/pdf/MT-93-01.pdf

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