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An Overview of Additive Manufacturing, Part II

This article is the second part in a two-part series on additive manufacturing. It presents a brief introduction to several additive manufacturing processes, such as electron beam melting, selective laser sintering and three-dimensional printing. The first installment in this two-part series was published in AMMTIAC Quarterly, *Vol. 4, No. 2, which is available online at http://ammtiac.alionscience.com/quarterly.* - Editor

INTRODUCTION

Additive manufacturing (AM) refers to a process that builds up a component in layers, as opposed to a subtractive operation, which removes matter from a block of material to form a product.[1,2] An increase in customer demand for customizable, quick turnaround, low cost products has opened the door for AM processes to enter the large scale production market once dominated by subtractive processes. Compared to AM, subtractive operations have relatively high capital costs and limited product design flexibility. This article provides an overview of several AM processes and presents current and emerging applications and the benefit of AM technology for the commercial and defense industries.

POWDER-BASED ADDITIVE MANUFACTURING

Powder-based AM processes build layers of metallic and plastic materials by dispersing powders on a substrate. Similar to the liquid-based processes, the powder is then cured by an ultraviolet (UV) light source (usually a laser). Powder-based processes, like Laser Engineered Net Shaping™ (LENS), have found widespread use in the fabrication and repair of metallic components because of their ability to deposit metal on an existing substrate. The following sections describe in more detail the processes listed in Table 1.

Electron Beam Melting

Electron beam melting (EBM) was developed in the late 1990s and is used primarily in the development of fully-dense, functional, metallic components. The EBM process uses an electron beam gun to create molten layers from metallic powder in a vacuum setting.[6] Each cross-sectional layer is outlined according to a computer-aided design (CAD) drawing. While the layer is still warm, the surrounding area is heated and the next layer of metallic powder is applied. By heating the surrounding area, the powdered particulate is sintered, preventing material repulsion and improving the material quality of the downfacing surface.[7] With the ability to create fully-dense, metallic components EBM is used for the production of parts that require high strength properties.

Table 1. Examples of additive manufacturing processes and materials.[3-5]

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
H-13 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

As shown in Table 1, titanium and steel alloys are typically used for the EBM process, and thus it is ideal for the development of metallic components that have complex surface geometries. In addition, EBM can produce both thick- and thin-walled structures. This is ideal for applications, such as components for the aerospace and automotive industries, which require low volume production of thin-walled parts that possess the strength properties of titanium and steel alloys. The ability to fabricate complex titanium components has also resulted in the use of EBM for the production of knee implants and bone plates in humans and animals.[7] More applications of EBM are listed in Table 2.

Table 2. Industrial applications of electron beam melting.[8-12]

Industry	Application
Medical	Canine knee implants Hip replacements
Aerospace	Landing gear components Impellers
Automotive	Turbocharger compressor wheels

Laser Engineered Net Shaping

Developed by Sandia National Laboratory in the mid 1990s, Laser Engineered Net Shaping™ is a process for creating near-net shape metallic structures.[13] Parts are fabricated by dispersing powdered metal over a molten pool of metal substrate. The molten substrate is created by a neodymium-doped yttrium aluminum garnet (ND:YAG) laser that operates at 500-600W in a closed argon gas* system.[14,15] The powder and laser dispersion pattern is dictated by a corresponding CAD model. The molten material solidifies and cools very quickly, resulting in materials that are fully dense.[16]

The LENS™ process (demonstrated in Figure 1) is capable of producing materials that possess mechanical properties similar to or better than those for homogenous materials (see Table 3) as a result of their densities.[16] The ability to create fully-dense components eliminates the need for heat-treatment after processing, thereby

Table 3. Comparison of mechanical properties for wrought homogenous materials and LENS-produced materials.[17]

Material	Ultimate Tensile Strength (ksi)		Yield Strength (ksi)		Percent Elongation	
	Wrought	LENS	Wrought	LENS	Wrought	LENS
316 Stainless Steel	85	110	34	63	50	46
304L Stainless Steel	-	95	40	47	55	70
H-13 Tool Steel	250	247	210	212	12	1-3
Annealed Ti-6Al-4V	135	130-145	124	120-140	10	1-16
Inconel 718	200	203	168	162	20	16

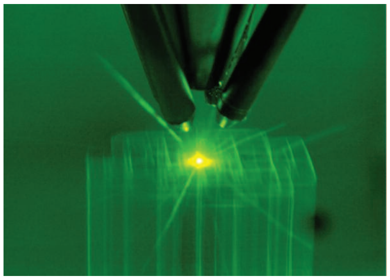

Figure 1. Four nozzles deliver powder sintered by a laser beam into a Sandia thunderbird logo design. (Photo by Randy Montoya and provided courtesy of Sandia)

reducing processing steps and time.[18] In addition, LENS™ can produce components with complex geometries, which makes it an optimal solution for the fabrication of new or the repair of used components.

LENS™ has several applications, but the two most popular are low volume, custom production runs and repairs to existing components. Certain parts, particularly components that have thin walls, have been saved from the scrap pile by the LENS™ process. Since LENS™ can produce a heat affected zone as small as 50 microns, it does not significantly deform or weaken the substrate material.[19] The DoD has employed LENS™ on several occasions to perform major repairs. At the Anniston Army Depot, LENS™ was used to repair gas turbines on M1 Abrams Tanks.[19] LENS™ has also been utilized as a type of 'hybrid' manufacturing process because of its ability to add high-resolution features to forged and cast components (see Table 4).[20] In addition, LENS™ can be employed to protect surfaces through the application of several layers of wear-resistant materials.

Table 4. Industrial applications of Laser Engineered Net Shaping.™ [21]

Industry	Application
Tool and Die	Rapid production of improved mold designs
Defense	In-field repair of damaged components
	Low volume production of specialty and hard-to-find parts
Medical	Load-bearing implants

Selective Laser Sintering

Developed in the mid-1980s, selective laser sintering (SLS) added a new dimension of versatility to AM technologies. For example, SLS can produce components from elastomers, thermoplastics, and metals. The metallic laser sintering process is referred to as direct metal laser sintering (DMLS).

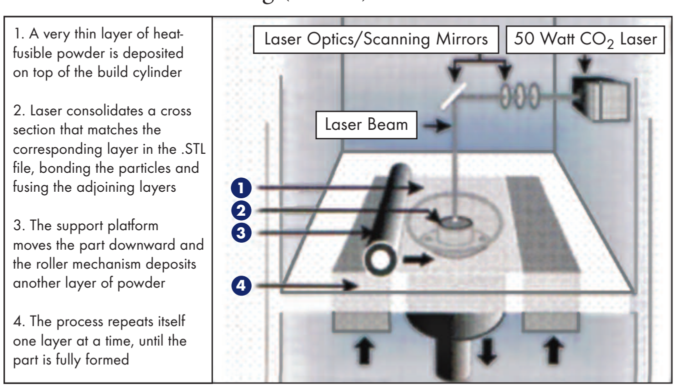

Figure 2. Selective laser sintering process.[3]

Table 5. Industrial applications of selective laser sintering.[24-28]

Industry	Company
Racing	Prototype fuel vent manifold Prototype air intake Production of race car exterior components
Athletic Wear	Functional prototype of running shoe
Mechanical	Functional prototype for riveting system
Architecture	3D scale model of building
Lawn care	Functional mower deck prototype
Electronic surveillance	Production of radar housing and components
Medical	Customized knee implants Customized dental implants Humeral mount for prosthesis
Automotive	Gearbox housing components
Aerospace	Engine components

In the SLS process (illustrated in Figure 2), a powdered material is deposited over a surface and then melted and fused by a carbon dioxide (CO_2) laser that moves in a pattern dictated by a CAD model. Sintering of the powder facilitates adhesion to the layer below. This process is repeated until the component is fully formed. While in the sintering phase, a metal component can receive additional heat treatment or can be infiltrated with a different metal (e.g., bronze in steel).[3] Components that are produced using SLS usually require no additional processing after the sintering process is completed.

The wide range of materials (detailed in Table 1) has made SLS one of the most widely utilized AM technologies. Based on the type of material used in a given SLS process, a prototype component can be fabricated to analyze fit and form and then tested in real time to assess functionality. SLS has become the option of choice over traditional machining processes for low volume or 'one off' production runs as a result of the ability to develop fully-functioning components. For example, SLS technologies were used to produce a fuel-vent manifold for first article testing on a carbon composite race car. SLS was chosen because it could produce the required complex geometries in less time and at a lower cost than acquiring conventional tools for the low volume production.[22] In addition, parts can be produced simultaneously in the SLS process, making larger volume production a reality. However, the components produced using SLS tend to be porous and have a rough surface finish.[23]

Three Dimensional Printing

Developed in the late 1980s, three dimensional printing (3DP) is a process that uses an inkjet system to deposit a low-viscosity binder onto a powdered-material bed through the use of a pattern derived from a CAD model (see Figure 3). Once the binder has dried, the completed part is removed from the machine and any excess powder is removed.[7] Plastic components will usually be infiltrated with a wax or epoxy resin after curing in order to improve the ability of the part to withstand mechanical stresses.[29] Commonly used for prototyping, 3DP has gained popularity as a method of producing mold cavities for investment cast-

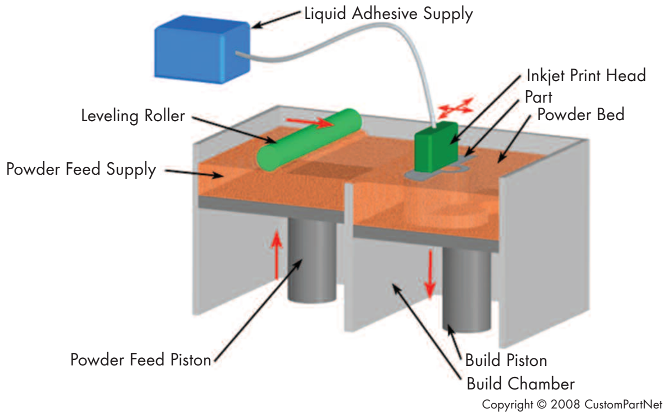

Figure 3. **Three-dimensional printing process. (Image courtesy of CustomPartNet, Copyright © 2008)[31]**

Table 6. **Industries and applications for three dimensional printing.[34]**

Industry	Application
Power tools	Functioning model for ergonomic testing
Architecture	Scale model of facilities
Motorcycle	Functional model of accessories for mock-up
Home and office furniture	Functional model of furniture designs
Pumping	Functional model of pump housing
Underwater exploration	Modeling of redesigned diving equipment

ing, and as a viable method of rapid tool production. In addition, 3DP technologies set themselves apart from other AM processes in that they can produce rigid, thin-walled parts. For example, printing systems like PolyJet Printing can produce parts with wall thicknesses of less than 1 mm.[30]

The wide range of 3DP applications (shown in Table 6) is a direct result of the types of materials that can be printed (e.g., metal, plastic, sand, and wax). The ability to use wax and sand in the printing process has led to the creation of more complex mold cavities. Similar to stereolithography and LOM, these materials are less susceptible to the effects of thermal expansion during the development of a mold cavity than injection molded processes. A detailed list of 3DP materials is shown in Table 1.

One example of using 3DP to create molded parts is the direct shell production casting (DSPC) process. In DSPC, a thin layer of aluminum is laid down with a roller and a silica binder material is sprayed over the aluminum. Once the layers are built up into a completed "green" mold, the mold is fired in preparation of accepting molten metal.[32] DSPC has been used primarily in the development of engine components (e.g., intake manifolds, cylinder heads, and fuel injectors), but it can also be used to cast parts similar to those produced via investment or sand casting.[33]

BENEFITS TO THE DOD

The ability to produce and repair high-strength, metallic parts has made AM a valuable technology throughout the Department of Defense (DoD). Advances in electronic controls and modeling interfaces has improved the reliability and repeatability of these AM processes to the point that they can be reliable for making repairs or fabricating replacement components for critical applications. As weapon systems across the services increase in age, the availability of certain components has decreased significantly. The challenge of supplying an adequate amount of these components to repair depots and intermediate repair facilities is a challenge that the use of AM technologies can help mitigate. The addition of an AM machine tool to a repair facility would help improve the availability of a weapon system by reducing the amount of time and energy spent trying to procure hard to find components. In cases where metallic components are heavily worn, bent, or gouged, processes like LENS and EBM can be used to bring components back to their original dimensions with comparable physical properties to the homogenous materials.

Several DoD organizations have employed AM processes with varying degrees of success. The Naval Undersea Warfare Center (NUWC) at Keyport, WA, operates the Rapid Manufacturing and Repair (RMR) program. This program employs SLS, DMLS, FDM, and EBM in the fabrication or repair of legacy parts and tooling.[35] For example, under the RMR program, AM processes were used in the production of door handles for the UH-60 helicopter. As a result of employing these processes, savings of $1.4 million were realized. The RMR program has been able to achieve an average return on investment of 10:1 over the life of the program, demonstrating that AM processes are not only a performance benefit, but a cost-savings benefit to the DoD.[35]

The US Army Aviation & Missile Research, Development & Engineering Center (AMRDEC) at Redstone Arsenal, AL, houses the Prototype Integration Facility (PIF) which employs several AM processes. Through the use of stereolithography†, fused deposition modeling†, laminated object manufacturing†, LENS™, SLS, and three-dimensional printing, AMRDEC is able to perform design verification and optimization studies in less time and at a lower cost than previous design assessment techniques. To assess ergonomic features and performance, AMRDEC used stereolithography to fabricate missile control joysticks for field testing. As a result of using stereolithography, the large time and setup costs associated with traditional production setup were avoided, thereby reducing the overall product cost and reducing the duration of the development process.

A joint DoD-industry effort recently employed a stereolithography-like fabrication process for the rapid production of titanium structural components. The process, called laser additive manufacturing (LAM), was able to produce titanium components 80% faster than traditional titanium fabrication processes.[36] The speed with which LAM can produce components made it an excellent candidate for the production of titanium replacement pylon ribs on the F-15 Strike Eagle. The original F-15 ribs, made from aluminum, were failing prematurely and the spare inventory was severely depleted due to forward deployment of the F-15 in Iraq and Afghanistan. Titanium was chosen as a replacement material for aluminum in the rib design, as it had greater strength properties than aluminum. Using LAM, the surge in part demand was met within two months, keeping aircraft availability at a maximum.[37] As a result of the success of this effort, LAM was awarded the 2003 Defense Manufacturing Technology Achievement Award.

SUMMARY

Advances in materials, electronics, modeling interfaces, and material distribution over the last two decades have vaulted AM processes from a simple method for producing three-dimensional plastic design prototypes to a viable option for low-volume production of metallic and plastic parts. Using processes like stereolithography, three-dimensional printing, fused deposition modeling, and selective laser sintering, plastic components can be produced to visualize an idea, ensure that newly designed components will fit together correctly, and help meet a fluctuating demand in production pieces. Laminated object manufacturing is used in the production of mold cavities for the rapid production of tools and other cast parts. Electron beam melting and Laser Engineered Net Shaping™ have made a significant impact on the ability to repair damaged parts, as they can build metallic materials on top of an existing substrate. In addition, the ability of EBM and LENS™ to also build new, fully-dense parts has helped to mitigate shortages of hard-to-find parts. Additive manufacturing technology helped to revolutionize the design process in the latter part of the 20th century with the advent of rapid prototyping processes. As these technologies continue to evolve in the 21st century, they will revolutionize the way parts are manufactured in the same way AM changed how parts were designed and conceptualized.

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

NOTES & REFERENCES

*Argon gas is used to prevent oxidation during the deposition process.

†These processes are described in Reference [1]

[1] Fink, C.W., "An Overview of Additive Manufacturing, Part I," *AMMTIAC Quarterly*, Vol. 4, No. 2, 2009.

[2] "What is Direct Digital Manufacturing?", Society of Manufacturing Engineers, www.sme.org/ddm, accessed May 2009.

[3] Freitag, D., T. Wohlers, and T. Philippi, *Rapid Prototyping: State of the Art*, Advanced Materials, Manufacturing, and Testing Information Analysis Center (formerly the Manufacturing Technology Information Analysis Center), 2003.

[4] Mueller, B., and D. Kochan, "Laminated Object Manufacturing for Rapid Tooling and Patternmaking in Foundry Industry," *Computers in Industry*, Vol. 39, No. 1, 1999, pp. 47-53.

[5] "Applications," Arcam AB, http://www.arcam.com/applications/othermaterials.asp, accessed May 2009.

[6] Lindhe, U., M. Larsson, and O. Harryson, "Rapid Manufacturing with Electron Beam Melting (EBM) – A Manufacturing Revolution," *Direct Metal Forum, Society of Manufacturing Engineers*, 2003.

[7] Gibson, I., *Advanced Manufacturing Technology for Medical Applications - Reverse Engineering, Software Conversion and Rapid Prototyping*, John Wiley & Sons, 2005.

[8] "New Orthopaedic Implants Improve People's Quality of Life," *Rapid News*, Arcam AB, http://www.arcam.com/Downloads/PDF/Arcam_Fixa_Ti-Por_Case_Study.pdf.

[9] "Successful Skull Reconstruction with Rapid Manufacturing," *Rapid News*, Arcam AB, http://www.arcam.com/Downloads/articles/Arcam%20-%20Maastricht%20Implant%20Case%20Study.pdf.

[10] "Prototal Uses Rapid Manufacturing of Customized Implants for Oral Surgery," *Rapid News*, Arcam AB, http://www.arcam.com/Downloads/articles/Arcam%20-%20Prototal%20Case%20Study.pdf.

[11] "Aerospace Applications," Arcam AB, http://www.arcam.com/applications/aerospace.asp, accessed April 2009.

[12] Cormier, D.R., O.L.A. Harrysson, and H. West, "Characterization of High Alloy Steel Produced Via Electron Beam Melting," *Solid Freeform Fabrication Symposium*, pp. 440-441, 2003.

[13] Singer, N., "Intense Hopes: Ten Companies Team to Commercialize Sandia's Powder-to-Parts Net Shaping Technology," *Sandia Lab News*, December 5, 1997, http://www.sandia.gov/LabNews/LN12-05-97/lens_story.html.

[14] Paschotta, R., *Encyclopedia of Laser Physics and Technology*, Wiley-VCH, 2008.

[15] Kumar, S., and B. Stucker, "Development of a Co-Cr-Mo to Tantalum Transition Using LENS for Orthopedic Applications," *Solid Freeform Fabrication Symposium*, 2005.

[16] Grylls, R., "Laser Engineered Net Shapes," *Advanced Materials and Processes*, Vol. 161, No. 6, p. 46, January 2003.

[17] "Manufacturing Technologies: Laser Engineered Net Shaping," Sandia National Laboratories, http://www.sandia.gov/mst/technologies/net-shaping.html, accessed April 2009.

[18] Ploude, R., "Laser-Based Repair System Reclaims High Value Military Components," NATO RTO-MP-AVT-109, *RTO-AVT Specialists Meeting – The Control and Reduction of Wear in Military Platforms, 2003*, DTIC Doc. ADA441707.

[19] Grylis, R., "Laser System Saves Damaged Military Parts from the Scrap Heap," *The Fabricator*, 27 February 2003, http://www.thefabricator.com/LaserCutting/LaserCutting_Article.cfm?ID=523.

[20] "LENS Aerospace & Defense," Optomec, Inc., http://www.optomec.com/site/lens_2, accessed April 2009.

[21] "The Use of Laser Engineered Net Shaping for Rapid Manufacturing of Dies with Protective Coatings and Improved Thermal Management," Industrial Technologies Program, Office of Energy Efficiency and Renewable Energy, US Department of Energy, July 2005.

[22] "Advanced Processes and Materials Help Indy Racing League Racecar," 3D Systems, Inc., http://www.3dsystems.com/products/datafiles/success_stories/Elan_Motorsports_APP_CS.pdf, accessed April 2009.

[23] Jack, H., "Selective Laser Sintering," *Engineering on a Disk*, Vol. 1, Grand Valley State University, August 2001, http://www.eod.gvsu.edu/eod/manufact/manufact-309.html.

[24] "Selective Laser Sintering Applications & Case Studies," 3D Systems, Inc., http://www.3dsystems.com/products/sls/applications.asp, accessed April 2009.

[25] "SLS Case Studies," 3T RPD, LTD., http://www.3trpd.co.uk/sls-case-studies.htm, accessed April 2009.

[26] "e-Manufacturing Solutions for the Orthopedic Market," EOS, http://www.eos.info/en/applications/medical/orthopedic-implants.html, accessed April 2009.

[27] "DirectPart Examples," EOS, http://www.eos.info/en/applications/target-metal-parts/directpart-examples.html, accessed April 2009.

[28] "Medical Devices," EOS, http://www.eos.info/en/applications/medical/medical-devices.html, accessed April 2009.

[29] Gebhardt, A., *Rapid Prototyping*, Hanser Gardner Publications, 2003.

[30] "Connex500 – The First Multi-Material 3D Printing System," Objet, Inc., http://www.objet.com/Products/Connex500/, accessed April 2009.

[31] "3D Printing," CustomPartNet, http://www.custompartnet.com/wu/3d-printing, accessed June 2009.

[32] "Direct Shell Production Casting," Design Prototyping Technologies, Inc., http://www.dpt-fast.com/knowledge/direct_shell_production_casting.asp, accessed May 2009.

[33] "Soligen: Technical Presentations and Case Studies," Soligen, http://www.soligen.com/about/casestudies.shtml, accessed May 2009.

[34] "3D Printer Success Stories," Stratasys, Inc., http://www.dimensionprinting.com/successstories/successstories-main.aspx, accessed April 2009.

[35] Delisle, R., M. Tobler, and K. Morris, "Rapid Manufacturing & Repair Phase II," *Commercial Technologies for Maintenance Activities Symposium*, National Center for Manufacturing Studies, 2008, http://techcon.ncms.org/Symposium2008/presentations/Plenary%20RM&R%20ctma%20baltimore-vs3%20REV%204-4.pdf.

[36] "2003 Defense Manufacturing Technology Achievement Award Recipients," DoD Manufacturing Technology Program, https://www.dodmantech.com/award/CY03/index.asp?main=award, accessed August 2009.

[37] "DoD Recognizes Manufacturing Technology Advancements," Defense AT&L, March-April 2004, pp. 92-94, http://www.dau.mil/pubs/dam/dam0204/acq-ma04.pdf.

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