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Technical Report

Technical Overview of Additive Manufacturing

by

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Additive manufacturing (AM) describes layer-by-layer manufacturing processes that build parts directly from a digital 3D model. Additive processes can be contrasted with conventional subtractive processes, such as the mill and lathe, where material is removed from a billet to create a part. The ability to build products through layers can offer advantages such as rapid creation of geometrically complex parts in a single build, minimal tooling requirements and material waste, and unattended around-the-clock production. The various AM processes are characterized by their raw material form and deposition process; these factors determine characteristics such as process speed, mechanical properties, part quality, post-processing requirements, build envelope, and cost. The purpose of this report is to provide persons unfamiliar with AM an overview of the available processes, their benefits, advantages, and disadvantages. The AM processes that will be discussed are binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization. The presented information was gathered through a literature search of relevant articles, discussions with those working in AM both inside and outside of the Department of Defense, and site visits to select locations.

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Administrative Information

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Abstract

Additive manufacturing (AM) describes layer-by-layer manufacturing processes that build parts directly from a digital 3D model. Additive processes can be contrasted with conventional subtractive processes, such as milling, where material is removed from a billet to create a part. The ability to build products through layers can offer advantages such as rapid creation of geometrically complex parts in a single build, minimal tooling requirements and material waste, and unattended around-the-clock production. The various AM processes are characterized by their raw material form and deposition process; these factors determine characteristics such as process speed, mechanical properties, part quality, post-processing requirements, build envelope, and cost. The purpose of this report is to provide persons unfamiliar with AM an overview of the available processes, their benefits, advantages, and disadvantages. The AM processes that will be discussed are binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization. The presented information was gathered through a literature search of relevant articles, discussions with those working in AM both inside and outside of the Department of Defense, and site visits to select locations.

Introduction

Additive manufacturing (AM) describes layer-by-layer manufacturing processes that build parts directly from a digital 3D model. Additive processes can be contrasted with conventional subtractive processes, such as milling, where material is removed from a billet to create a part as shown in Figure 1. The ability to build products through layers can offer advantages such as rapid creation of geometrically complex parts in a single build, minimal tooling requirements and material waste, and unattended around-the-clock production. The various AM processes are characterized by their raw material form and deposition process; these factors determine characteristics such as process speed, mechanical properties, part quality, post-processing requirements, build envelope, and cost [1].

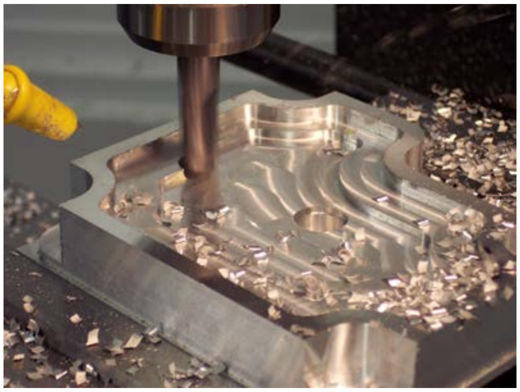

Figure 1. Milling: a subtractive manufacturing process [2].

Additive manufacturing (AM) describes manufacturing processes in use since the mid-1980s that build solid parts by adding material in layers. While the various AM processes are characterized by their raw material form and deposition process, the progression of moving from an idea to a finished product is the same for all AM processes as provided below [1]:

- computer-aided design (CAD) file development
- CAD file conversion into a usable STL file format
- file transfer to the AM system
- AM system set-up
- product fabrication (layer-by-layer deposition)
- part removal
- post-processing

An example of the product fabrication step is shown in Figure 2 as accomplished on a vat polymerization AM system. After the 3D CAD model has been loaded into the AM system, the CAD model is digitally sliced into thin layers that are physically deposited layer-by-layer through selective curing of a liquid photopolymer until the entire 3D CAD model has been deposited as a finished shape [3]. After the part is removed, the post-processing includes cleaning excess photopolymer out of the part’s cavities and a final material cure under ultraviolet light.

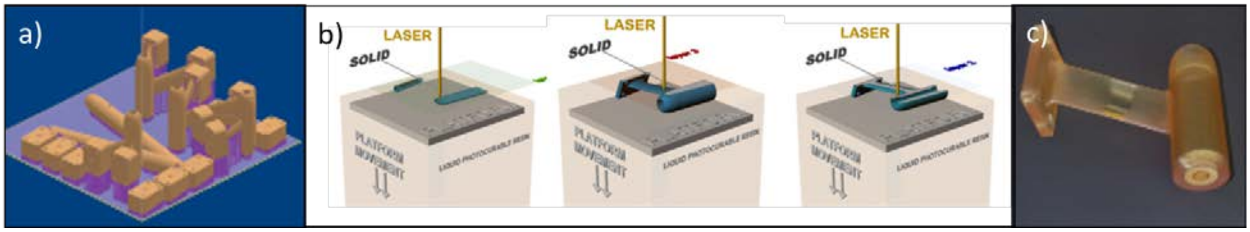

Figure 2. AM parts are created by a) developing a CAD model, b) physical depositing layers of the CAD file, and c) finishing the part.

While the layer deposition manner varies depending on the AM process, all begin with a digital model and end with a physical part created in layers. Two-dimensional printed drawings are unnecessary and tooling is only required during the build process in hybridized AM systems that combine AM with a subtractive process (such as sheet lamination).

Leaps in AM development occurred in the late 1980s and early 1990s. During this time, current well-known AM companies, such as Stratasys and EOS, were founded and new AM technologies, such as material extrusion, laser-based, and inkjet printing systems, began to appear [4]. Since then, significant work in materials and process research and development has occurred. Both the quality and choice of materials have expanded to include not only polymers but also ceramics, metals, and electronic materials. The AM industry has spread worldwide with the US leading in companies specializing in polymeric materials while European companies lead in the manufacture of metallic materials [5].

Common names for AM include 3D printing, rapid prototyping (RP), and direct digital manufacturing (DDM). While AM is interchangeable with the term 3D printing, RP generally refers to prototype-specific applications (the term was developed as early AM technology was used to create polymer prototypes) while DDM is generally used in discussions of AM of end-use parts.

Additive Manufacturing Overview

Additive manufacturing can be subdivided into the following seven categories [3]:

- binder jetting
- directed energy deposition (DED)
- material extrusion
- material jetting
- powder bed fusion (PBF)
- sheet lamination
- vat polymerization

Individual factors such as speed, cost, available materials, deposition rate, part quality, post-processing requirements, and common defects vary significantly between processes. As such, specific processes should be chosen based on the requirements of the end application. Table 1 links general materials and raw material forms available for each process. Electronic specific materials are not included in this table. Table 2 provides common-use names for select AM processes. Often, what were originally manufacturing trade names (such as fused deposition modeling by Stratasys) have become synonymous with an entire AM process category. Finally, Table 3 provides a summary of the materials, advantages, disadvantages, and post-processing requirements for each of the processes.

Table 1. AM by Material and Raw Form

Raw Form	**Material**	**Powder Bed Fusion**	**Directed Energy Deposition**	**Material Extrusion**	**Material Jetting**	**Vat Polymerization**	**Sheet Lamination**	**Binder Jetting**
Powder	Metal	X	X					X
	Polymer	X						X
	Ceramic							X
	Sand							X
Filament/Wire	Metal		X					
	Polymer			X				
Epoxy	Polymer				X	X		
Other	Metal Sheet						X	
	Paper Sheet						X	
	Wax				X			

Table 2. Common Usage/ Trade Names for AM Processes

Form	Material	Powder Bed Fusion	Directed Energy Deposition	Material Extrusion	Sheet Lamination	Vat Polymerization
Powder	Metal	Direct metal laser sintering (DMLS)[1] Electron beam melting (EB)[2] Selective laser melting (SLM) Laser melting (LM)	Laser engineered net shaping (LENS)[4]			
	Polymer	Selective laser sintering (SLS)[3]				
Filament	Metal		Direct metal (DM) Direct metal deposition (DMD) Laser metal deposition (LMD)			
	Polymer			Fused deposition modeling (FDM)[5] Fused filament fabrication		
Epoxy	Polymer					Stereolithography (SLA)
Sheet					Ultrasonic consolidation (UC)	

[1] EOS [2] Arcam [3] 3D Systems [4] Optomec [5] Stratasys

Table 3. Additive Manufacturing Processes Summary

Process	Material	Advantages	Disadvantages	Post-Processing		Manufacturers	Notes
				Steps	Effort		
Binder Jetting	Metal Polymer Ceramic Sand	Full color printing (non-metal) Rapid Majority of unused material is recyclable Multi-material (when infiltration is used in post-processing)	Multi-step process requiring multiple machines (metal) Post-processing can be significant (metal)	Sintering, powder removal , and metal infiltration required for metals Powder removal and sealant applied on exterior of non-metallic parts	High	ExOne Voxeljet ZCorp	
Directed Energy Deposition	Metal	High deposition rate Material additions Large parts Could be performed through modification of existing robotic systems (wire only)	Low resolution High thermal stresses Limited geometries Significant post-processing required Potential hazardous material (e.g. powder Ti), gases, and energy sources (lasers, electron beams, etc.) Not portable Systems are not in place to capture unused material (powder based systems)	Surface finishing Heat treatment Machining required (removal from base plate and finishing)	High	AeroMet DM3D Keystone Synergistic Enterprises, Inc. Optomec Sciaky	Material cost is higher for power than for wire processes

Table 3. Additive Manufacturing Processes Summary (cont.)

Process	Material	Advantages	Disadvantages	Post-Processing		Manufacturers	Notes
				Steps	Effort		
Material Extrusion	Polymer	Inexpensive Hobbyist systems available Rapid Limited post-processing requirements “Safe” process (many systems could be kept in an office environment) Smaller systems are portable Could be performed through modification of existing robotic systems Colors available	Limited geometries Significant quality decrease in hobbyist systems	Support material removal Chemical smoothing of outer surface may be required	Low	3D Systems Stratasys Various manufactures of small-scale systems	Machine cost varies significantly (small systems are low cost) Material cost varies significantly
Material Jetting	Polymer Wax	Variable stiffness within parts Colors available Limited post-processing requirements “Safe” process (many systems could be kept in an office environment) Smaller systems are portable Smooth surface finish Multi-material parts	Limited range of materials Parts can be fragile	Support material removal	Low	3D Systems Stratasys	

Table 3. Additive Manufacturing Processes Summary (cont.)

Process	Material	Advantages	Disadvantages	Post-Processing		Manufacturers	Notes
				Steps	Effort		
Material Jetting	Polymer Wax	Variable stiffness within parts Colors available Limited post-processing requirements “Safe” process (many systems could be kept in an office environment) Smaller systems are portable Smooth surface finish Multi-material parts	Limited range of materials	Support material removal	Low	3D Systems Stratasys	
Powder Bed Fusion	Metal Polymer Ceramic Sand	Relatively fine resolution Material recyclable (metal)	Slow Small build envelope Large thermal gradients Unused material is generally not recyclable (polymers) Significant post-processing can be required Potential hazardous material (e.g. powder Ti), gases, and energy sources (lasers, electron beams, etc.) Not portable	Surface finishing Heat treatment (metal) Powder removal Support material removal	High	3D Systems Arcam Concept Laser EOS/Morris Technologies Phenix Systems Realizer Renishaw SLM Solutions	Material cost is high System cost is high

Table 3. Additive Manufacturing Processes Summary (cont.)

Process	Material	Advantages	Disadvantages	Post-Processing		Manufacturers	Notes
				Steps	Effort		
Sheet Lamination	Metal Paper	Limited 3D geometries Inexpensive (paper) Color printing (paper) Embed electronics in cavities during build Limited post-processing requirements Portable (paper) “Safe” process for paper (could be kept in an office environment) Inexpensive readily available material (paper) Multi-material (metal)	Not portable (metal systems) Unused material is generally not recyclable	Heat treatment may be required for metals Machining is performed during the build process Excess paper must be removed	Low	Mcor Fabrisonic	Paper machines are low cost
Vat Polymerization	Polymer	Large parts Fine resolution Majority of unused material is recyclable	Post-processing is messy Not portable	Surface cure Support material removal Excess liquid removal	Medium	3D Systems Asiga Materialise	Material cost is higher for power than for wire processes

Technical Additive Manufacturing Process Descriptions

This section provides detailed descriptions of each of the seven AM processes: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization.

Binder Jetting

How it Works

Binder jetting is "an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials" [3]. Binder jetting uses a binder to "glue" powder together in the shape of a part. The process begins by spreading a base layer of powder over the working envelope. The powder layer is followed by a laterally moving print head (that applies the binder to the powder) followed by a heating element (to set the binder). The working envelope is then lowered one layer and the process is repeated until the part is completed. Depending on whether the binder is meant to remain in the final part material, multi-step post-processing may be required.

Figure 3. Binder jetting system [6].

If the binder will be part of the final part, the powder tray encasing the part will be removed from the machine and the excess powder blown away. The final part is then removed and a sealant applied to the surface and cured to finish the part.

When the binder is required only as the first step in creating a fully dense part, such as with metal powders, significant post-processing including curing, depowdering, sintering, infiltrating, annealing, and finishing is required. In these cases, the undisturbed part, still within the initial build box, is first cured in an oven several hours to overnight to harden the binder. Once cured, the part goes through a depowdering process where loose powder is dislodged, blown, and vacuumed away. The still fragile part is then carefully placed in a furnace to be sintered at high temperatures to both burn off the binder and metallurgically bond the metal particles together. After sintering, while the part can be easily handled, the binder removal leaves the part with as low as half density. To increase the density, the part is infiltrated by wicking a lower melting temperature metal into the part. The part is then annealed to increase mechanical properties and the surfaces finished using processes including peening, blasting, electroplating, and sanding.

Even when post-processing is considered, the binder jetting process is rapid, relatively inexpensive, and is one of the few 3D printing processes capable of printing in full color. These advantages make binder jetting an excellent choice for parts that rely on visual features, graphics, and colors. For nonmetallic materials, the lack of environmental hazards (e.g. gases, metal powder) and fewer post-processing requirements make binder jetting ideal in office spaces, as the machines are considered safe and quiet without producing odors. Concept and presentation models, package development, fixtures, small scale industrial parts, medical models, working assemblies, and low volume production parts are all potential applications. Metal parts have been made for use as casting prototypes, gear boxes, fuel tanks, transmission housings, lightweight engine parts, and structural hinges. An example of sand casting and the resultant part is shown in Figure 4.

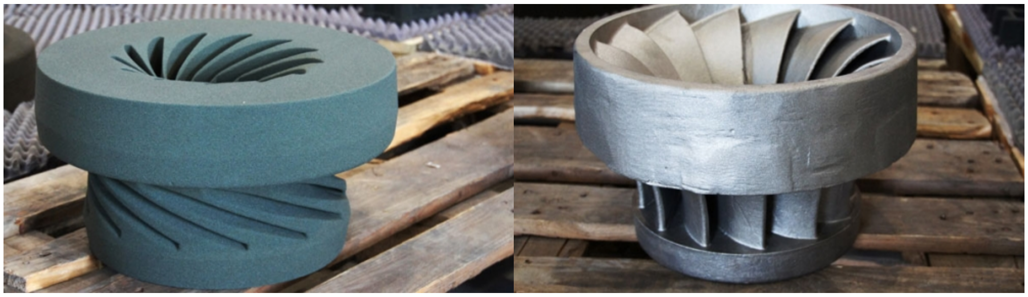

Figure 4. Sand cast and final part by Voxeljet Technology GmbH [7].

Materials

Examples of materials available for binder jetted AM systems include the following:

- Stainless steel
- Carbon steel
- Bronze
- Tungsten
- Soda lime glass
- Sand
- Various polymers in powder form

Example Applications

An example application where AM has been used in place of a traditional process is in fabrication of stators for use in the mining industry. The traditionally manufactured steel stators were rapidly degrading after continual exposure to mining abrasives. To solve this problem, ExOne’s binder jetting process was used to fabricate stators that are a mix of stainless steel and bronze. The new stators have significantly increased service life in comparison to the conventional parts. Figure 5 shows the observable wear in a conventionally manufactured stator after 100-200 in-service hours and the corresponding AM part at 600 in-service hours with no measurable wear [8]. The ability to produce such gradient materials is a significant achievement in AM.

Figure 5. From left: wear in conventionally machined 4145 steel stator after 200-300 hours; 3D printed part showing no measurable wear after 600 hours [6].

The process is also used by Walter Reed National Military Medical Center to create guides for difficult surgeries. A patient's CAT scans are used to create 3D CAD models of the region of interest and then printed out, in color, to scale. The guides allow surgeons to identify problem areas and surgical routes thereby reducing both the surgical time and the patient healing time.

Directed Energy Deposition

How it Works

Directed energy deposition (DED) is "an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as the material is being deposited" [3]. A directed energy source (such as a laser, electron beam, or plasma arc) is used to produce a melt pool and then material (wire or powder) is injected into the melt pool [9]. The material is deposited in a raster motion and new layers are added by adjusting the vertical height of the machine. During deposition, an inert shielding gas is used to prevent the material from reacting with atmospheric elements.

After the part is made, post-processing heat treatments and surface finishing are required. At a minimum, the part must be removed from the metal substrate it was built on (often performed using a wire electrical discharge machine). Wire DED systems can deposit material quickly. As a result, the part or repair is often oversized and then machined down to the desired dimensions and surface finish. Small finishing details, such as holes and threads, are completed during post-build processing as they can normally be made more quickly, accurately, and inexpensively by traditional processes. An example of a Ti component being considered for usage in the Joint Strike Fighter (JSF) is shown in Figure 6 [10].

Figure 6. Ti component made by Sciaky for potential use in the Joint Strike Fighter (JSF) program [10].

Materials

Theoretically, any weldable material available in a powder or wire form that is compatible with the available machines can be used. DED systems that use both powder and wire are available. Generally, the cost associated with wire is low as welding wire is a common and relatively inexpensive consumable. Discussions with companies have found them open to trying new materials. The material quality varies depending on the material and the specific system used. As an example, Optomec indicates its LENS system is capable of producing parts with as-cast properties [11]. Examples of materials available for DED systems include the following:

- Various steels
- Ti alloys
- Ni alloys
- Tantalum

Advantages and Disadvantages

How quickly material can be deposited directly influences the time required to move from uploading a CAD file to the finished part. DED offers some of the highest deposition rates of all AM process due to the use of wire as a material form. The exact material deposition rate varies widely depending on the material, energy source, whether the machine uses wire or powder, the desired quality of the part, and feature sizes. In general, electron beam sources deposit at significantly higher rates than laser. The highest deposition rates are seen when standard gas metal arc welding (GMAW) robots are used to lay down material such as shown in Figure 7 [12].

Figure 7. Canfield University gas metal arc welding robot depositing material [13].

The ability to rapidly deposit material in a large envelope significantly increases the potential size and weight of a manufactured part. At these high deposition rates, finished or “near net shape” parts are not desired. Instead, a “near shape” part is deposited with post- build machining used to finish. In this case, while machining is required, the time and material saved by building up material only in required areas saves significant labor time, material, and cost over machining from a standard billet.

The powder-based DED processes do not obtain the high deposition rates seen in the wire systems. These systems allow precise deposition of small amounts of material. Powders can also be mixed during the deposition process allowing deposition of controlled material gradients or multiple materials [11]. Additionally, the majority of excess powder collected during the deposition process can be reused.

The ability to add material to a part creates applications in both repair and part development. For repair purposes, DED can be used to salvage worn-down expensive parts by building up the worn areas. Material can also be added to fix manufacturing mistakes (such as overmachining). Adding material in this manner can save time, labor, and money depending on the difficulty and cost of creating a new part. Material can also be added to modify existing parts or as part of the regular construction process.

While speed, large parts, and material gradients are advantages of DED, there are also a number of disadvantages. As the deposition rates are high, the part detail is sacrificed requiring post-build machining. Residual stresses build up in the material and microstructure deficiencies often require heat treatment; these problems are generally exacerbated in the higher deposition rate processes. No inherent support structure in the build prohibits the easy building of difficult geometric features such as overhangs. When required, such features can be made when the part is housed on a five or more axis CNC machine. Environmental and safety concerns must also be considered as gases, powders, and energy sources (e.g. lasers) are required.

Material Extrusion

How it Works

Material extrusion is “an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice” [3]. Material extrusion uses a heated nozzle to soften material and then pushes the material through the nozzle and onto the substrate. As the material is extruded from the nozzle, the substrate or the nozzle moves laterally to deposit material in the desired locations, as shown in Figure 8. Layer build-up occurs by changing the vertical placement of the part between passes. The simple process, which has been called a "glorified glue gun", is commonly called fused deposition modeling (FDM) a term coined by Stratasys Inc., the inventor of the technology.

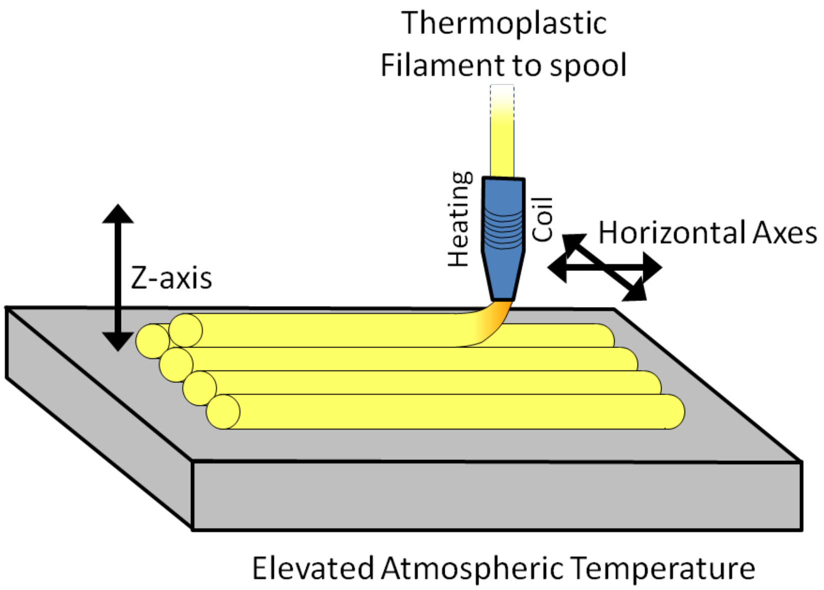

Figure 8. Schematic of the material extrusion process where filament is deposited using a heated extruder nozzle.

Unlike many other AM systems, parts made using material extrusion require no major post-processing beyond removal of support material (some of which can be dissolved in water). While part surfaces can be smoothed chemically or physically, finished parts can often be printed and used directly. The surface can be finished, but a groove is left behind between each deposited layer. Material extrusion systems are easy to use and require minimal maintenance beyond routine nozzle adjustments. While commercial systems are kept at elevated temperatures to reduce thermal gradients in the final part, a special atmosphere is not strictly required and many hobbyist systems operate in open air. Additionally, some advanced systems monitor the amount of material deposited, will seamlessly switch between different filaments, and alert the user via text message or e-mail when the part is complete or when more material is needed.

Materials

Currently, most material choices are restricted to thermoplastics, although low melting temperature metals (such as solders) are being explored in academia [14]. Material comes in spools with some available in different colors; however, only research machines and a few commercial systems are capable of switching materials or colors during printing. All the materials are engineered to be shelf stable and not require curing or turn brittle. In general, the part properties are not isotropic, with the z-direction being weakest.

When overhanging structures are built, a separate structural material is deposited. Structural material is often water soluble and only requires immersion in an ultrasonic water bath to dissolve the material. Occasionally, the support material will fail or the parts will warp during deposition. Materials research is ongoing in the development of new materials and monitoring. An example of current materials research is at Oak Ridge National Laboratory where incorporating carbon fiber into materials is hoped to decrease anisotropic properties and thermal expansion issues [15]. Examples of materials available for material extrusion systems include the following:

- Acrylonitrile butadiene styrene (ABS plastic)
- Polycarbonate (PC)
- Polyetherimide
- PPSF-PPSU (Polyphenylsulfone)
- ULTEM

Of the available materials, most are not fully certified for ship use as they cannot currently pass flame, smoke, and toxicity tests (ASTM E162: Flame Spread, ASTM E662: Smoke Density, and Fire Toxicity Test) or melting debris and flaming droplets requirements (DDS 078-71 and Military Standard 2031). Only ULTEM is currently capable of passing these tests although it will melt at higher temperatures.

Advantages and Disadvantages

While thin layer thicknesses are available, machines with large build envelopes sacrifice layer thickness and resolution for speed and size. Currently, the system with the largest build volume is offered by Stratasys (3’ x 2’ x 3’) as shown in Figure 9. When larger parts are required, they can be glued or fused together. There is no current push to expand the build envelope; instead, companies are focusing on improving other aspects of the process such as material quality, speed, and resolution. Build speeds vary depending on the layer resolution and are also extremely dependent on part geometry and build layout. Horizontally oriented parts print significantly faster than vertically oreinted parts. Time savings can also be achieved by hollowing parts or creating an internal support network instead of building fully dense parts. In general, the greatest speeds are achieved by batch loading machines and leaving them to run from half a day, full day, or overnight to maximize efficiency.

A disadvantage is that available machines do not include feedback loops and, in cases of warping or support, material failure deposition will still continue leading to material waste and potential damage of the nozzle.

Figure 9. Stratasys Fortus printer showing the large 3’ x 2’ x 3’ build volume (picture taken at UTEP, courtesy of Francisco Medina).

Applications

Roughly half of the applications for material extruded products are prototypes and models. A quarter of the market consists of master patterns to be used for sand casting, creation of complicated metal parts, or hydroforming tools. End-use parts are also routinely made, often as replacement parts for existing systems. Parts can be made as short-term functional replacements while more durable parts are developed. Some examples of end-use parts are custom NASA Rover parts and medical devices (hearing aids, custom supports).

Material Jetting

How it Works

Material jetting is “an additive manufacturing process in which droplets of build material are selectively deposited” [3]. Material jetting describes processes that use printing heads to deposit droplets of UV curable material. After deposition, a leveling blade is run over the deposited droplets to create a smooth surface. Immediately after being printed, most materials are cured using a UV lamp. After one layer has been printed, the system drops the part one layer thickness and the process is repeated. Material jetting has a unique capability to print multiple material properties (material variations) within a single part by varying the types of polymer deposited. Depending on the pattern of the deposited droplets and whether droplets of multiple materials are used, the area can be stiff or flexible. According to Stratasys, the Objet Connex 3D printers are capable of printing up to 14 material variations within a run [16]. A schematic of the process is shown in Figure 10.

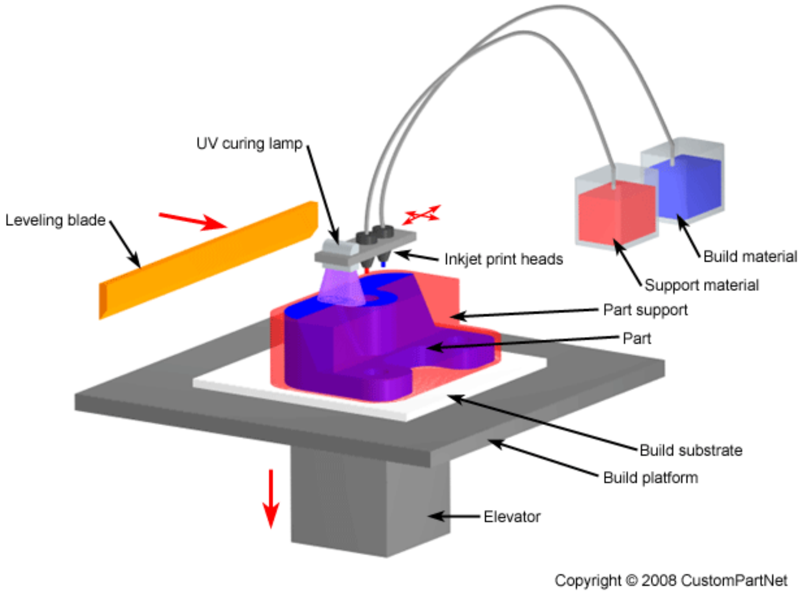

Figure 10. Material jetting schematic [17].

Post-processing for material jetted polymer parts is minimal. No post-printing final cure is required and the part is printed with a smooth finish. As a result, parts can generally be used immediately after printing. While support material can be required, it is water soluble and can be removed by hand with water immersion.

Materials

The materials currently available for material jetting processes are UV curable acrylic resins and wax. The UV curable acrylic material comes in resin form in cartridges. Stratasys Objet Connex offers 17 different materials capable of being combined to produce 123 distinct materials with unique properties [18]. A number of wax-like thermoplastics are available from Solidscape.

Advantages and Disadvantages

Material jetting advantages include high resolution, smooth surface finish, flexible parts, material property gradients within one part, translucent and colored parts, and minimal post-processing requirements.

Applications

Due to high resolution and finish, material jetting is used for making wax molds for jewelry, dental, and research applications; an example of wax molds later used to create parts for a Bently Blower model are shown in Figure 11. The wax molds are used to cast materials including gold, silver, steel, and bronze.

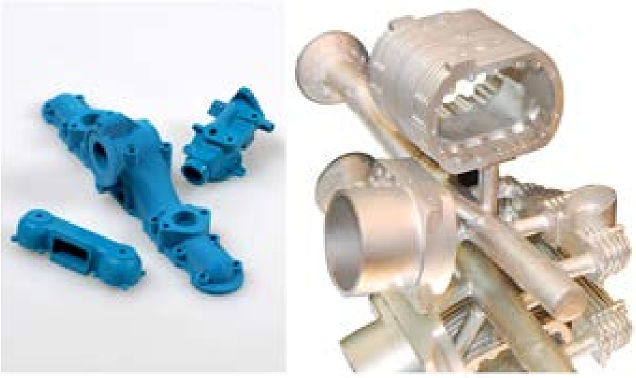

Figure 11. Wax 1:5 scale molds for the Bently Blower and the final model [19].

Powder Bed Fusion

How it Works

Powder bed fusion is “an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed” [3]. Powder bed fusion (PBF) uses an energy source (such as a laser) to fuse together powder contained in a bed. The process uses two beds of powder: one where the part is built and one holding the reserve powder. As shown in Figure 12, powder from the reserve bed is spread into the build area and is selectively melted into one layer of the product. To create more layers, the build area and the reserve bed move downward and upward respectively and the spreading and melting process is repeated. Selective laser sintering (SLS) machines are lower power and use polymers while direct metal laser sintering (DMLS) and other melting processes such as electron beam (EB) use metals.

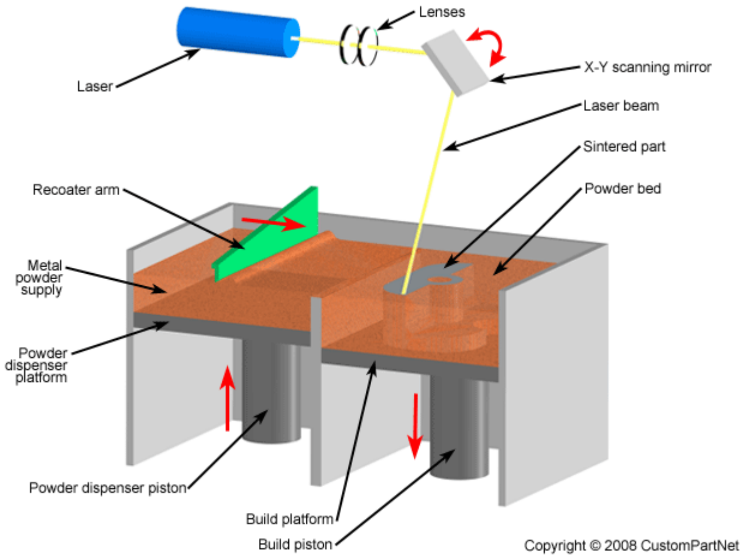

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Figure 12. Powder bed fusion process [17].

After the build is complete, the excess powder is blown out or otherwise removed. While unused non-metallic powders must be discarded, unused metallic powder can be recycled and used in future builds resulting in little overall waste. After the build is completed, the loose powder surrounding the part must be removed; powder can become trapped in small crevices or holes in the part and be difficult to remove. Once the powder is removed, metallic parts must be machined (often using a wire EDM) from the base plate. Hot isostatic pressing (HIP) can be used to reduce porosity in the built material. Heat treating to remove residual stresses and obtain the desired microstructure is often required; Ti EB parts do not require this step as the build chamber maintains temperatures such that microstructural integrity is maintained. Finally, the as-built surface finish is rough and requires finishing (e.g. abrasive blasting, shot peening, electrochemical polishing, abrasive flow machining, electroplating, etc.) [20]. Examples of PBF parts with and without surface finishing are shown in Figure 13.

Figure 13. Powder bed fusion bolts with finished and unfinished surfaces [20].

Materials

Systems have been designed for both metallic and nonmetallic materials. New materials specific to AM are also being developed. The quality of the resulting parts is reported by some companies to be 99.5% dense with near wrought properties depending on the material. However, as with other AM processes, available material data from a variety of independent sources depends greatly on the specific PBF process and material. Examples of materials available for PBF processes include the following:

- Various steels
- Ti alloys
- Ni alloys
- Various polymers

Advantages and Disadvantages

PBF systems are capable of making geometrically-complex parts as the powder that is not used during the build can be used to support the part. As a result, complex structures can be designed and built that are not possible using other AM methods (such as a ball within a ball or assembled structures). While metallic powders can often be reused, non-metallic powders cannot. Significant post-processing time can be required. Some unique additions to parts can be achieved, including raised barcodes (with a contrast ink applied post-build), buttons, glue lines, integrated hinges, snap clips, and threading [21].

Envelope size is a limitation of PBF. Due to the small layer thicknesses and high resolution, increasing the part size increases build times; as a result, smaller build envelopes are customary. Larger build envelopes also require more powder to fill the reserve bed and longer stroke times to apply the powder. Work is currently being performed both in industry and academia to reduce powder spreading time and increase the directed energy pass rate. To increase productivity, the number and orientation of parts are controlled to make the most use of space. As with other processes, the orientation of the part within the build is critical to ensure even weight distribution and to prevent warping or heavier parts from falling in on themselves.

Applications

PBF has been used recently by the National Aeronautics and Space Administration to fabricate an injector. The component allowed for record amounts of thrust to be achieved during testing. A significant achievement in the project was reducing the number of components from 115 down to 2 by using AM [22].

In the medical field, EB has been used since 2007 to manufacture Ti hip implants. Unlike other processes, EB can create a rough surface on the acetabular cup that bone can easily attach to. The implants, created by Arcam, have been approved for usage in Europe and the U.S. and over 30,000 were implanted by 2012 [23]. Sixteen Ti-6Al-4V acetabular cups can be made in one build over a 12 hour period.

At the University of Southampton in the United Kingdom (UK) researchers designed an efficient lightweight airplane structure capable of being rapidly assembled. In July 2011, they flew the world’s first printed aircraft, the Southampton University Laser Sintered Aircraft (SULSA). The vehicle structure was printed in sections and then assembled, without tools in about 10 minutes. The aircraft, shown in Figure 14, flew for approximately 30 minutes and reached speeds approaching 100 mph. The vehicle was made using an EOS EOSINT P730 nylon laser sintering machine. The researchers cited the ability to create idealized complex shapes without the associated traditional manufacturing costs as a driver in using an additive manufacturing process [24, 25]. Since then, other universities, such as the University of Leeds sponsored by EADS (the makers of Airbus), have created prototype unmanned air vehicles (UAV) [26].

Figure 14. SULSA is the world's first "printed" aircraft. The University of Southampton printed the UAV structure allowing the entire vehicle to be assembled in about 10 minutes without tools [24, 25].

Sheet Lamination

How It Works.

Sheet lamination is “an additive manufacturing process in which sheets of material are bonded to form an object” [3]. To create a part, material is laid out in thin strips that are then bonded together. After bonding, machining, cutting, or trimming of the material occurs leaving the finished shape. Sheet lamination is a hybrid AM process as it builds in layers but requires subtractive processes to shape the final part. A schematic of the process is shown in Figure 15.

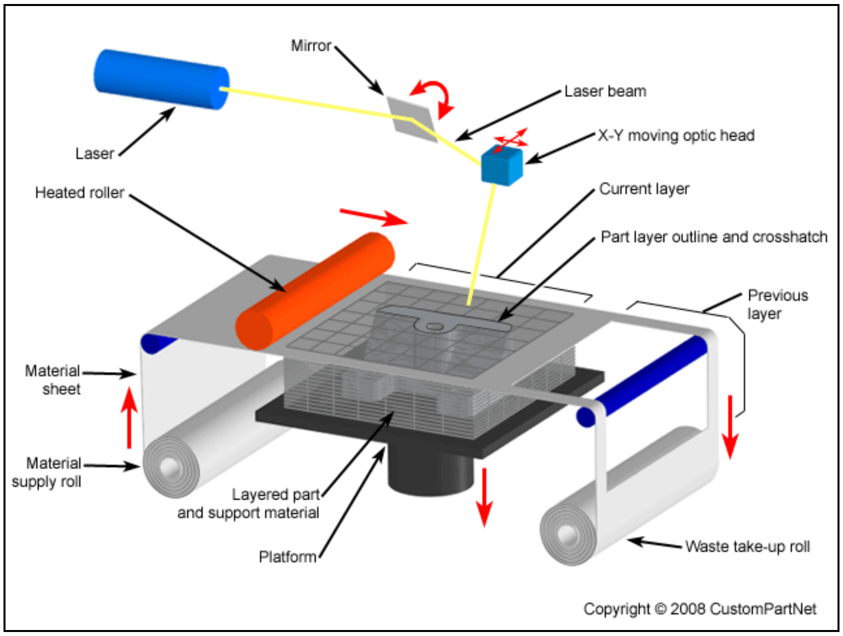

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Figure 15. Sheet lamination [17].

Metal sheet lamination is commonly called ultrasonic consolidation (UC) as the process uses ultrasonic welding principles. The thin sheets of metal are compressed and vibrated ultrasonically at the surface by a sonatrode. The compression and vibration of the metal strips at these high frequencies leads to interfacial heating (up to 50% of the material melting temperature) and, ultimately, to atomic diffusion and metallurgical bonding the metal strips [27].

When paper is used, several sheets are initially bonded together to create a base layer. After this layer is complete, adhesive is selectively applied to the base layer and a sheet is place on top of the adhesive. The highest density of adhesive is applied within the part cross-section. The adhesive layer is activated when a heated roller presses the sheets together. At this stage, if coloring is to be applied, it is now performed. After the sheet is fully bonded, the single sheet is cut to the desired shape and the process repeats. Once completed, the excess material is removed by hand. This process is aided by the selectively applied adhesive and "dicing" of waste material by the system before part removal [28].

Materials

Paper, plastic, and metal materials are available. Paper and plastic sheets are typically bonded with an adhesive. Ceramic sheets and metal green tapes are bonded together via heat treatment (i.e. built up objects are fired in a furnace). Metal sheets are bonded through either welding (e.g. ultrasonic welding) or bolting.

In theory, metal based processes can be used to create functionally-graded and multi-material parts; however, there is little information available and the majority of the work is being performed on 3000 series Al alloys [29]. The majority of work is being performed at the research level.

Advantages and Disadvantages

A unique advantage of sheet lamination is the ability to "insert pre-fabricated components (such as thermal management devices, sensors, computational devices, heat pipes, etc.) into machined cavities of the part under construction" prior to adding any finishing material [29]. Unlike other metallic AM processes, UC uses low temperature consolidation, thereby reducing high temperature defects, thermal gradients, and allowing integration of sensors containing lower melting temperature materials.

Applications

UC has been used to fabricate panels for satellites and injection molding tools. Some work has been performed in functionally-graded material, metal-matrix composites, and fiber embedded structures [27]. In the case of satellite panels, an SBIR was funded through Phase II resulting in a finished panel as shown in Figure 16 [30].

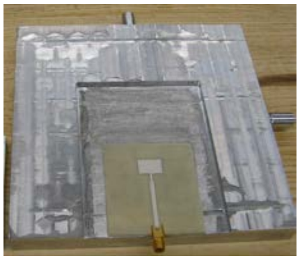

Figure 16. Ultrasonic consolidation and direct write: finished panel with embedded honeycomb and external patch antenna [30].

Vat Polymerization

How it Works

Vat polymerization is “an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization” [3]. The vat polymerization process is unique in that it makes solid parts from a liquid photopolymer. The technique has been traditionally referred to as stereolithography (SLA). Part building occurs in a vat filled with liquid photopolymer material where a movable perforated platform is placed one layer thickness below the surface of the liquid resin. As is shown in Figure 17, a UV light is scanned across the surface and cures the material in its path; the platform keeps the cured material in place. Once one layer has been completed, the platform is lowered the height of one layer thickness and a wiper evenly transfers the liquid photopolymer over the cured material. The UV curing and lowering of the platform are repeated until the part is finished. As with many other AM processes, the part is made from the bottom upward with the first printed layers consisting of support structure.

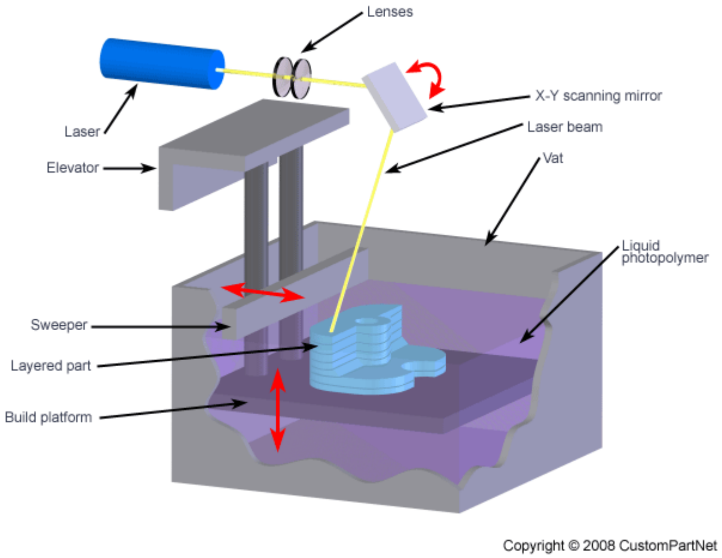

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Figure 17. Stereolithography [17].

After the build is complete, the newly printed parts are elevated above the liquid photopolymer and excess material is allowed to drain through the perforated platform and back into the vat. After the parts are removed from the build chamber, they are wiped down and placed in a curing chamber. While the material is hardened during the build, the curing step ensures the part surface is fully hardened. After curing, the support structure is snapped away from the part. The lightest support structures, such as those built inside holes and in voids to maintain overhanging shapes, can be easily removed by hand. The majority of uncured SLA material can be collected and reused after the build.

The build envelope, wiper speed, ultraviolet laser scanning speed, and speed of the platform determine the size of parts that can be built the speed at which they can be built. Large machines are available with build dimensions of up to 82.5 inches [31] with machines allowing lengths of 59 inches capable of producing parts up to 330 lbs [32].

Materials

The available materials are limited to photopolymers. The resin quality has increased in recent years with part quality now allowing not only prototypes but working parts. When desired, the printed parts can be coated with metal to improve their strength. Some materials are designed to mimic dental materials for tooth restoration applications or be suitable for jewelry casting while others are designated "high" temperature materials and are stable up to 130°C [33]. Additionally, transparent materials are available.

Using Additive Manufacturing

This section will examine the benefits of AM and provide examples of current usage and knowledge gaps.

Benefits

AM is used when it produces products faster, cheaper, and/or more easily than traditional manufacturing processes. In general, suitable applications for AM have the following characteristics:

- Low volume batches
- Complex geometry requirements
- Expensive or difficult to manufacture materials
- Rapid turnaround/design change requirements

While additional benefits obtained from using AM can include in-house control over the manufacturing process, unique material properties, reductions in material waste, and rapid part production; AM's primary benefits are achieved through design flexibility, time, and cost. It is noteworthy that specific advantages achieved through one AM process may not be achieved with another.

Design Flexibility

Geometry. In conventional manufacturing, designers are limited by the chosen manufacturing process (e.g., holes must be located in areas where drilling is feasible). In contrast, AM can create structures that cannot be fabricated using other methods; an example of such a structure is shown in Figure 18. While AM does have process specific design limitations (extent of overhangs, internal cavities, multi-materials, etc.), some of these limitations can be overcome with a knowledgeable operator.

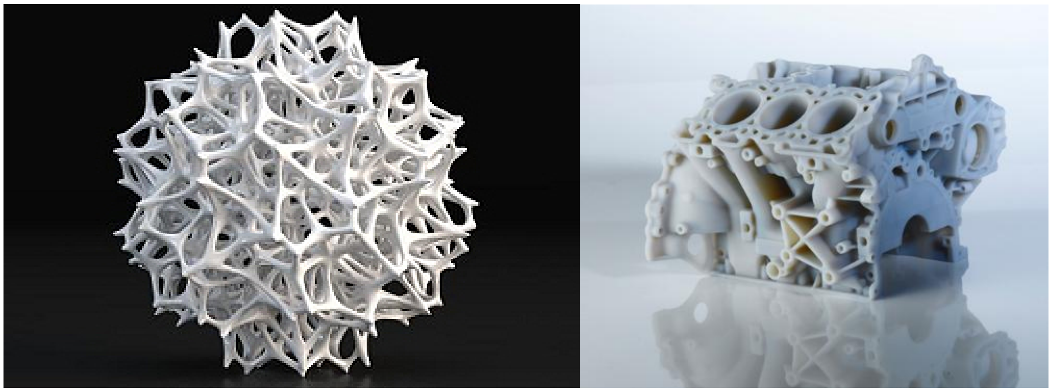

Figure 18. Left: An object only capable of being fabricated through 3D printing [34], Right: Eden 3D printed engine [35].

The most efficient part designs both reduce the number of moving parts and remove excess material. As there is minimal cost for complexity in AM, efficient designs, such as seen in the topology-optimized hinge in Figure 19, can be readily fabricated. Weight optimization can also be achieved through strategic internal cavities and hollowed-out parts. The ability to produce complex geometries can also be applied to printed working assemblies, consolidation of multiple parts, varying densities, buttons, hinges, raised barcodes, etc.

Figure 19. The background hinge was produced using conventional subtractive manufacturing techniques. The hinge in the foreground was produced using additive manufacturing techniques and is half the weight. The hinges were produced by EADS [36].

Materials. A wide range of materials are available for AM including metals, ceramics, and polymers. Plastic materials can be chosen based on their tensile strength, glass transition temperature, transparency, color, etc. Photopolymers and common plastics, including ABS and polycarbonates, are available with new materials with improved properties continually under development. A variety of metals including tool steels, stainless steels, Ti alloys, Ni alloys, Co-Cr alloys, and precious metals such as gold and silver can be printed. Materials come in a variety of forms including powder, filament, wire, and resin [5]. Some AM processes allow material gradients to be created within a single part.

An example of a multi-material application is shown in Figure 20 where the printed outer “rubber” portion of the wheel is more compliant than the stiffer internal spokes; however, the entire wheel was printed on one machine out of the same base materials with the differences in stiffness due to variations in material deposition [35]. Switching between different materials, in the same build is an ongoing area of research and development. The Massachusetts Institute of Technology’s (MIT) Self Assembly Lab has printed parts, shown in Figure 20, that change shape when exposed to water (layers of materials that expand in water force joints of nonexpandable material open or close). The result is what is known as a “4D” printed object with time and the environment acting as the fourth dimension [37].

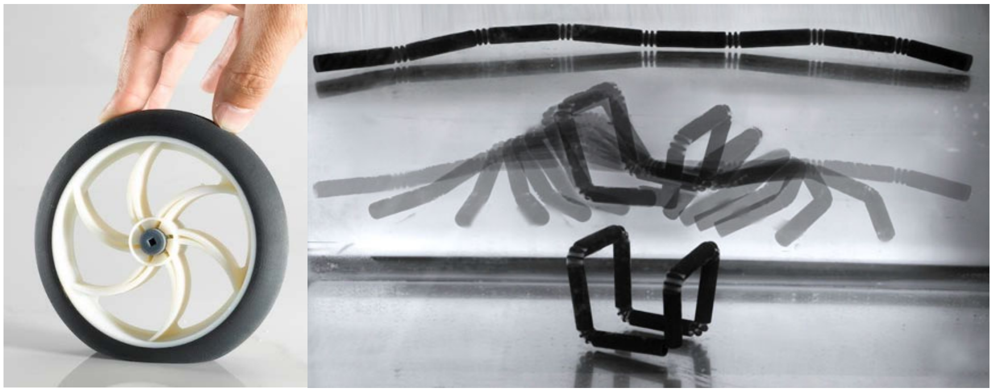

Figure 20. From left: Variable stiffness in the Connex 3D printed wheel [35]; multi-materials create 4D printed parts with self-folding strands into forming a 3D cube [37].

Time

AM can improve turnaround time by reducing the number of steps in the manufacturing process. Conventional prototype manufacturing requires the designer to confer with technicians at various stages of the process. With AM, as the designer can produce the 3D model that will be directly converted to a product, intermediate discussions and errors can be reduced or eliminated. Time devoted to development of custom tooling is also removed, allowing prototype iterations to be completed in a matter of days versus weeks or months. Additionally, designers can quickly alter digital models and then rebuild without having to wait for new tooling to be developed. Advanced technologies, such as 3D scanning, can further be combined with AM to rapidly create 3D CAD files of existing parts that are broken or missing drawings.

On-site 3D printing further reduces time. The expansive footprints of conventional manufacturing systems are not required for many AM processes allowing fabrication to occur in labs or even office environments. On-site fabrication eliminates or reduces time spent in contracting, shipping, delivery, and discussions. Outside of prototyping applications, similar mechanisms for time reduction are obtained in tooling, low volume production, and spare parts on demand.

While AM can significantly reduce the time required for prototyping, the majority of AM technologies are not as simple as pressing a button and waiting until the finished part is completed. Depending on the AM system, post-processing requirements can significantly increase part completion time. An example is metal powder bed fusion processes where, after the part has been built, cleaning, machining, surface finishing, and heat treatments can still be required; these are both time and labor intensive. Additionally, if complex AM systems are not operated by a well-trained technician, significant time will be wasted re-printing parts due to a variety of part deficiencies stemming from poor build envelope part placement and post-processing difficulties. Through discussions with various AM operators, it is estimated that it takes roughly a year (once a machine is fully operational) to learn the nuances of high end metal machines and consistently achieve quality parts.

Cost

Besides reducing time, AM can decrease costs through reductions in labor, raw material cost, specialized tooling requirements, and in-house manufacturing. Typical AM systems can run unattended with long builds programmed to run overnight or through weekends to maximize the production time of the machine. The number of personnel required to oversee an AM machine is low and the number of AM machines can often be increased without increasing operators. However, a critical component of the effective implementation of AM is a well-trained and experienced operator who understands the preferential placement of parts, geometric constraints, warping issues, etc. that can occur. The ability of the operator to quickly and accurately identify potential problems before starting the build saves the time, materials, and ultimately cost that would be consumed performing multiple runs to correct problems.

The raw material costs for AM systems vary dramatically depending on the desired material quality (high or low), form (powder, resin, filament, etc.), and system requirements. Many AM manufacturers require material to be purchased through them to preserve the warranty; once the machine warranty has expired, material can be sourced from multiple vendors at a lower cost. However, as (in general) the cost of an AM part is determined by the amount of material used (part weight) and not the associated part complexity, when considering two functionally equivalent parts, one geometrically complex but lightweight and one geometrically simple but heavier, the lightweight part will be cheaper to produce using AM. Simply put: with AM there is little to no cost for complexity. The reverse is seen with conventional manufacturing where designers must balance weight optimization with fabrication costs. Additionally, for some raw material forms (such as metallic powder), leftover material can be recycled and used in a future build.

AM offers significant cost reduction benefits by reducing, eliminating, or by producing required specialized tooling. When design changes are made, new parts can be modified or adjusted without associated tooling costs. Some AM processes can also be used to repair worn parts or machining errors.

Another area where AM creates cost savings is in the ability to manufacture parts in-house. In-house manufacture provides complete control over not only the design process but the fabrication process. Many of the steps required when working through contractors can be eliminated depending on the application and skill of the in-house operators.

Current Usage

AM technology is currently in use in the following fields: jewelry, footwear, industrial design, education, transportation, consumer products and electronics, architecture, engineering, construction, geographic information systems, automotive, aerospace, dental and medical, government and military, industrial machinery, etc. New AM applications are continually being identified due to increased customer exposure and quality improvements. The primary applications for AM can be broadly broken into the areas of rapid prototyping, rapid tooling, and rapid manufacturing. It must be stressed that the various AM process lend themselves to different applications as the quality, material, speed, etc. of each process is different. This is well illustrated in Figure 21 where powder bed fusion systems (in the lower left) can make small, high resolution parts while directed energy deposition systems (in the upper right) can make large, low resolution parts. Both systems fall under AM, but the two processes are suited to different applications [38].

Figure 21. Deposition Rate verses Resolution [38].

Prototyping

AM has been traditionally associated with the term “rapid prototyping” as the early systems were used to create prototypes for visualization, geometric fittings, and functional testing [17]. Prototypes can be rapidly designed and manufactured as visual aids, to check geometric issues, functional testing pieces, etc. When conventional manufacturing processes are used, design changes are difficult, costly, and time consuming (particularly when custom tooling must be used). Because AM does not require tooling during the build, designs can be rapidly developed, built, and modified at low cost. Once a design has been finalized, traditional large scale manufacturing methods can be used to cost effectively manufacture the product in large volumes.

Tooling

AM processes can be used to rapidly construct tooling such as molds and dies. Because AM builds the tooling and not the final part, AM’s benefits can be exploited while using the original material and process for the final part. Because of its unique geometric capabilities, design tooling features such as complex cooling channels can be easily incorporated. Custom fixtures, injection mold dies, sand cast molds, and sheet metal forming tools are all examples of tooling currently developed using AM.

Manufacturing

As AM part quality has improved, AM parts are increasingly being considered for end-use purposes. AM for end-use parts is known both as rapid manufacturing (RM) and direct digital manufacturing (DDM). The most effective use of AM for finished products occurs when material cost and part complexity are high and the final part is relatively small or when an outside vendor is unavailable. In general, conventional processes are more efficient when large parts, high production volumes, stringent tolerance requirements, and high material quality are required [17]. Currently, AM is most effective with low production volumes [17]. Concerns about part quality and lack of available standards and qualifications for AM parts are currently preventing widespread use of AM for DDM in certain sectors.

The medical sector is one area where AM’s ability to create parts difficult or impossible to manufacture using other methods can be readily implemented. A limited number of AM implants (both metal and polymer) have already been approved for use in both the US and in Europe [39]. In the aerospace field, AM is used to fabricate air ducts that are in use on multiple F/A18s [40].

Potential end-use parts are not limited to small products and interest in creating large scale structures, including for aircraft and housing applications, is ongoing. Boeing and the Council for Scientific and Industrial Research's (CSIR's) National Laser Centre (NLC) have formed a partnership to create large scale, complex Ti components (up to 78 inches in length) for aircraft usage. EADS, the company who designs the Airbus, is already using AM to create Ti aerospace parts and they have a goal of creating a printed plane by 2050, after significant advances in both materials and processing [41-43]. Contour crafting (CC), a process that lays down thick layers of paste that are shaped using trowels, as shown in Figure 22, was developed by the University of Southern California in an attempt to automate the building of dwellings, with potential applications in emergency, low-income, and commercial housing construction [44, 45]. Because of the simplicity of the process and the materials, CC has been considered as a means to develop infrastructure (e.g. roads, landing pads, shade walls, etc.) on the Moon or Mars. Large-scale demonstrations of the process for the National Aeronautics and Space Agency (NASA) have not moved forward at this time [46].

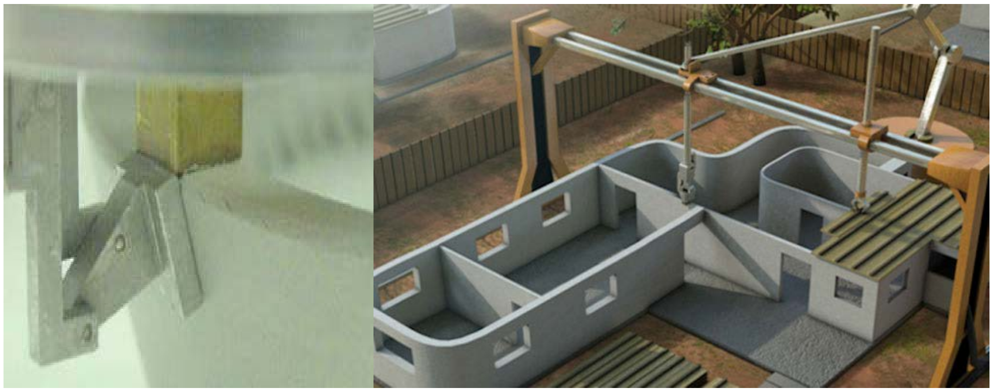

Figure 22. Contour crafting from left: back view of the contour crafting process [45], idealized house construction [44].

At Home Use

In recent years, the users of AM have shifted to include not only traditional companies, but also personal users. Fused deposition modeling (FDM), originally developed by Stratasys, is a simple AM process that requires little more than a heated nozzle and filament material to create a final part. Because the FDM process can be easily scaled to desktop-sized systems and does not require the same safety precautions as other processes, after the Stratasys patent for FDM expired, a dramatic increase in the number of home printing devices occurred. Internet communities dedicated to the distribution of AM CAD files and information pertinent to the at-home user have increased and hobbyists are now using personal AM systems to design new parts or to print components they would rather not purchase from a store. These hobbyist systems are helping expand the limits of 3D printing as many are open-source and allow individual users to tweak and refine parameters such as resolution, surface finish, printing speed, and build volume. The majority of the hobbyist systems can be purchased for under $2K [47]. Some available models are shown in Figure 23.

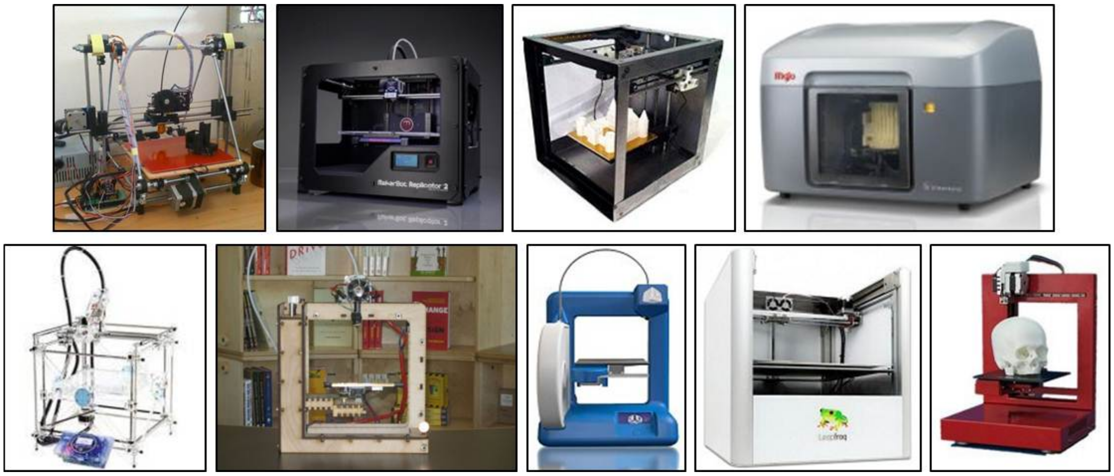

Figure 23. Hobbyist AM systems (from upper left): RepRap Prusa Mendel, MakerBot Replicator 2, Solidoodle 3, Stratasys Mojo, PP3D! UP, MakerGear M2, 3D Systems Cube, LeapFrog Creatr, and Bits from Bytes Rap Man.

Knowledge Gaps and Challenges

To address science and technology gaps in AM specifically as they relate to the Navy, the Naval Additive Manufacturing Technology Interchange (NAMTI), sponsored by the Office of Naval Research and hosted by Naval Sea Systems Command, Naval Air Systems Command, the Navy Research Laboratory, and the Navy Warfare Development Command was held in February 2014 hosted at NSWCCD. Break-out sessions in the areas of design innovations, advanced materials, rapid response to the warfighter, qualification and certification, and life-cycle sustainment were held to identify knowledge gaps and explore the timely insertion of AM technology into naval platforms.

America Makes, a public-private partnership and the first Institute for Manufacturing Innovation under the National Network for Manufacturing Innovation, is also funding projects to close the knowledge gaps that are preventing more widespread usage of AM.

Qualification and Certification

As AM is relatively new and as AM industry leaders have improved system and material quality and selection, particularly in regards to metals, the lack of standards and ability to rapidly qualify parts has increasingly become a concern. There are a very limited number of standards available directly related to AM processes. To address this problem, the American Society for Testing and Materials (ASTM) formed Technical Committee F42 on Additive Manufacturing Technologies. The committee was formed in 2009 and has created a limited number of standards related to design, materials and processes, terminology, and test methods [9, 48-50]. Their current emphasis is on powder bed fusion processes.

Machine variability is a concern and the problem is being pursued by the National Institute for Standards and Technology (NIST). Some of their current work has focused on examining the properties of metals manufactured using an EOS powder bed fusion system as well as the consistency of material properties between different machines. While the majority of their work has focused on steel, they will be expanding their work to include Ti alloys. One of their previous projects focused on development of a standard test piece that measures the system’s ability to create various geometrical features while maintaining dimensional accuracy. The test piece was designed using their EOS powder bed fusion system [51].

Non destructive evaluation is another area where little work has been performed. Common types of defects and the best method to evaluate them have not been identified. As a result, work must be performed examining the types of defects unique to AM, how these defects affect the part quality, acceptance criteria, and robust methods for identifying defects in parts.

The following is a summary of qualification and certification gaps:

- Rapid qualification of parts
- Non-destructive evaluation of parts
- Buy-in from shipyards and OEMs
- Identification of parts that can be made using AM
- Process monitoring and feedback
- Qualifying parts built in systems under rugged environments

Materials

As the majority of material property testing has been performed by individual companies, no extensive public database of material properties is available. Some materials processed with a specific AM technology (e.g., Ti-64 with a powder bed electron beam source) have been studied more extensively due to a wide variety of applications (e.g., medical, light weight structures); it is therefore easier to obtain data about these materials. The quality and consistency of the majority of materials remains an unknown. As such, a database of material properties is needed as well as study into advanced materials (electronic, magnetic, multi-material, etc.) [51].

Design

Design guides. Few design guides for AM currently exist. There is no current way of identifying the driving properties that determine when AM should be considered.

Printing systems. To print multi-material components or systems, multi-material printing is required. Currently, multi-material printing within the same build is being explored at the university level but is not currently in place in industry [14]. The ability to prevent not only multi-materials but also material gradients, dissimilar materials, etc. will increase design options with both parts and systems.

Machines must also be able to take interruptions in builds (due to power loss, etc.), realign themselves to the current build, and finish the component. While this has been achieved at some level, more work is required.

Data management. As parts or systems increase in complexity, the problem of data management increases. Increases in size and complexity of parts, particularly when making multimaterial builds, will increase file sizes and data management concerns. AM systems must allow for real-time monitoring and control of builds to maintain properties.

Rapid modeling of AM parts to predict material properties and unachievable features must also occur. Currently, well trained operators must be familiar with their own AM system and how parts will print to consistently achieve good results. Computer software that checks the feasibility of reliably printing the desired part is required to speed these checks on components.

The exceptional design freedom provided to designers is not likely realized in the field. Groups that may need parts may not have the CAD software or ability to make 3D drawings. A database of approved parts should be created that personnel can draw from. Work needs to be performed in managing such a database and identifying under what situations parts printed in this manner can be used.

Areas where further development is required include:

- Database of parts that can be made using AM
- CAD data storage
- Integration of CAD files into COTs software
- Design guides

Summary

While challenges remain for AM to become a common fabrication method for in-service parts, significant headway has been made and AM processes and materials continue to be refined. As this report is meant to guide those unfamiliar with AM technology and provide a starting point for further investigations, it is noteworthy that the technology is changing quickly. New materials and process refinements are persistent and various organizations are working to solve existing problems. However, while AM has opened new possibilities in manufacturing, whether AM is the best manufacturing method for a particular product must be determined based on the part to be made.

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