GUIDE TO ADDITIVE MANUFACTURING

Additive Manufacturing is changing the way manufacturing gets done, but what is it? How does it work? What are the benefits and limitations? What industries are benefiting the most? ITAMCO answers these questions and examines how 3D printing compares to traditional manufacturing.

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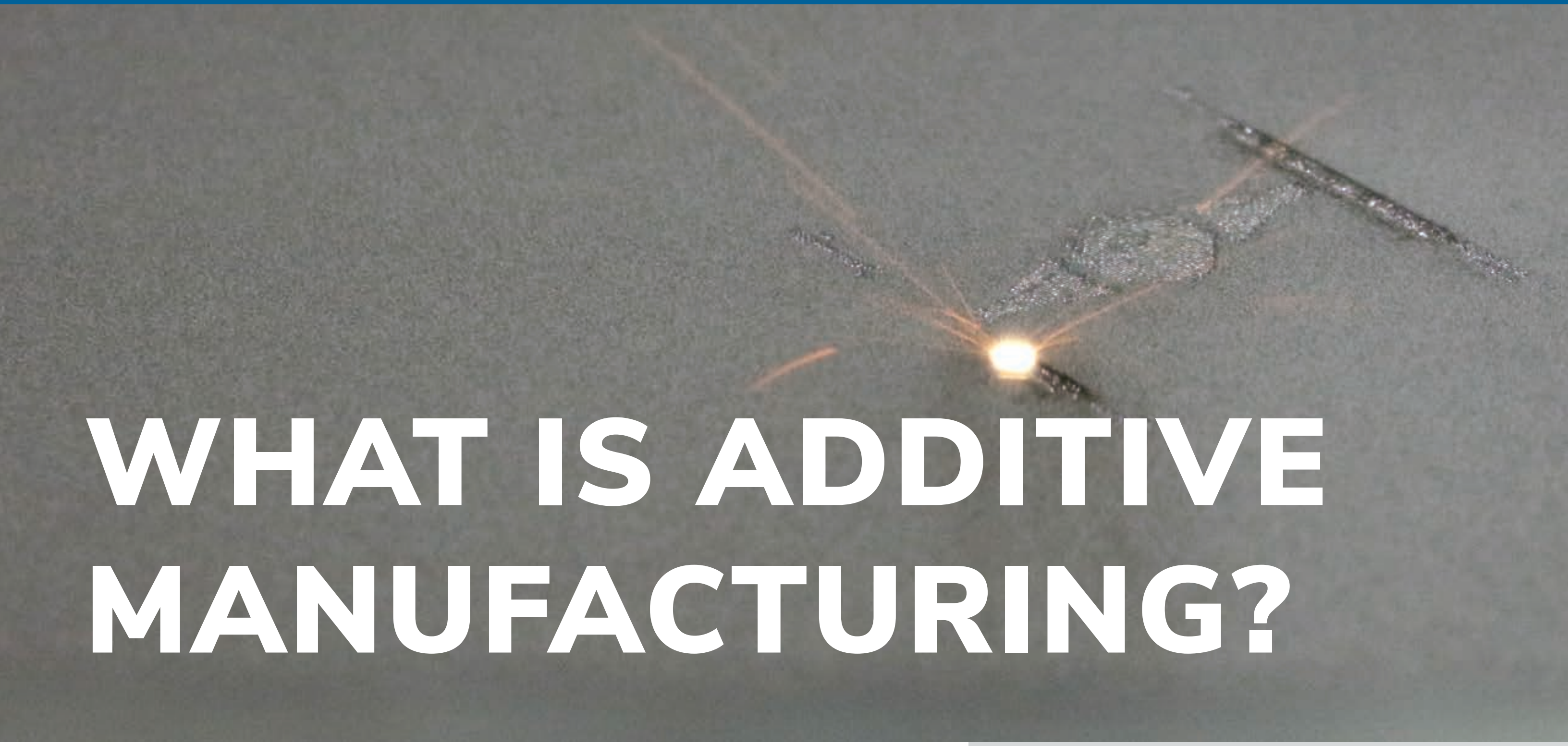


WHAT IS ADDITIVE MANUFACTURING?

Additive manufacturing (AM) or 3D printing is layer-by-layer fabrication of three-dimensional (3D) objects.

Traditional manufacturing is a subtractive process in which material is removed to produce the final shape. Examples include milling, cutting, turning, drilling, boring, etc. AM offers many advantages in the production of parts, but the key benefits are unparalleled design freedom, less hard tooling and assembly, and the ability to manufacture single or multiple components from a wide range of materials.

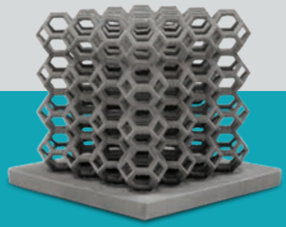
Surprisingly this seemingly modern technology has been around for nearly 40 years. In 1981 automatic methods for producing 3D models were detailed by Hideo Kodama. His published paper described techniques for forming 3D plastic models using ultraviolet (UV) cured layers of photopolymer material. In 1984 Chuck Hull filed a patent coining the term stereolithography, a technique utilizing UV light lasers and a bed or vat or photopolymer resin to produce 3D objects. In 1986, Hull co-founded 3D Systems, the first 3D printing company. In 1987 3D Systems commercializes the first 3D printer, the SLA-1 Stereolithography (SLA) printer, bringing additive manufacturing to the commercial market.

Early AM processes were established as a solution for faster product development or rapid prototyping, because the idea was to create 3D models or mock-ups to check form, fit, and function before beginning full production. While this is still the case in some situations, the applications for AM technology have increased along with the sophistication of the technology. High-strength metal parts are now possible with more materials being regularly added.

GROWING NEED FOR AM

AM now meets a broad range of needs throughout many industries including:

- Visualization tool or parts in design
- Means to create customized products
- Industrial tooling
- Small runs of production parts
- Full-strength, rapid prototyping
- Test complex geometries



ITAMCO AND AM

As an early adopter of AM, ITAMCO currently offers printing via the Powder Bed Fusion Method which has the versatility of using a variety of metals for the substrate. In addition, ITAMCO has been instrumental in creating software to help facilitate and simplify the AM design process through Atlas 3D. (page 6).

ADDITIVE MANUFACTURING PROCESSES

AM production techniques vary. The American Society for Testing and Materials (ASTM) grouped AM processes into these seven categories: Material Extrusion, Vat Polymerization, Powder Bed Fusion, Material Jetting, Binder Jetting, Directed Energy Deposition, and Sheet Lamination.

These seven AM processes include variations on the layered 3D printing concept. Material state (powder, liquid, filament), heat or light sources (laser, thermal, electron beam, plasma arc), number of print axes, feed systems, and build chamber characteristics all vary. Some additive manufacturing techniques require additional post-processing while others do not.

AM continues to make inroads across broad areas of manufacturing and industry. The types of materials AM can handle is constantly growing and includes the ability to print plastics, ceramics, glass, paper, wood, cement, and metals. Mckinsey & Company believes the overall economic impact created by AM could reach at least $100 billion by 2025.

Lets take a look at the six main AM processes.

SEVEN AM PROCESSES

1. **Material Extrusion:** Material selectively dispensed through a nozzle or orifice
2. **Vat Polymerization:** Liquid photopolymer in a vat is selectively cured by UV light
3. **Powder Bed Fusion:** High-energy source selectively fuses powder particles
4. **Material Jetting:** Droplets of material are selectively deposited and cured
5. **Binder Jetting:** Liquid bonding agent selectively binds regions of a powder bed
6. **Directed Energy Deposition:** A high-energy source fuses material as it is deposited

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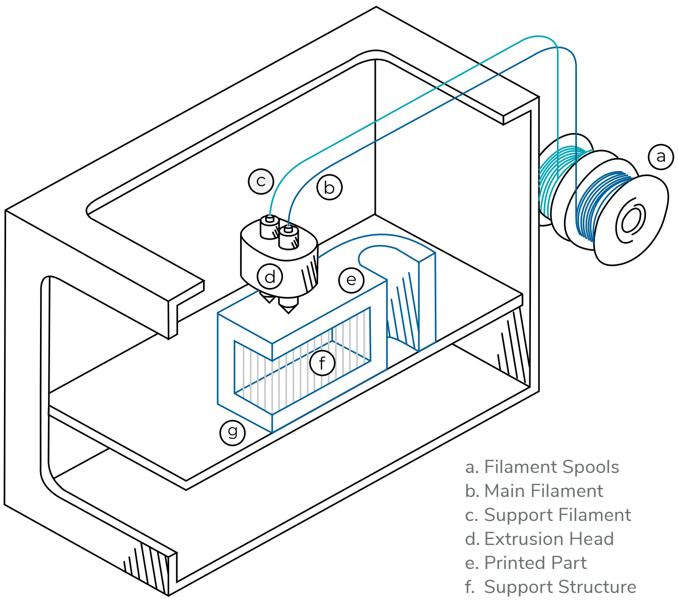
7. Sheet Lamination: Sheets of material are bonded and formed layer-by-layer

MATERIAL EXTRUSION



a. Filament Spools
b. Main Filament
c. Support Filament
d. Extrusion Head
e. Printed Part
f. Support Structure
g. Build Platform

One of the most common forms of material extrusion is Fused Deposition Modeling (FDM), and perhaps the best-known additive manufacturing process. FDM extrudes a thermoplastic filament through a heated nozzle and onto a build platform. The material then solidifies as it cools, although not until it fuses to adjacent layers. FDM uses a wide variety of thermoplastic filaments, including ABS, PLA, nylon, PC, ULTEM, and more complex filaments (metal and wood).

Because the process is fast and inexpensive, it is often used to produce prototypes. Although dimensional accuracy was a concern in the past, some modern industrial FDM machines produce functional prototypes. Research continues into post-processing methods which improve overall strength of the finished part.

APPLICATIONS

FDM is often the go-to method for producing non-functional prototypes or rapid prototyping where multiple iterations are needed because it is quick and cost effective. It is also the dominant technology behind lower-cost, hobbyist machines.

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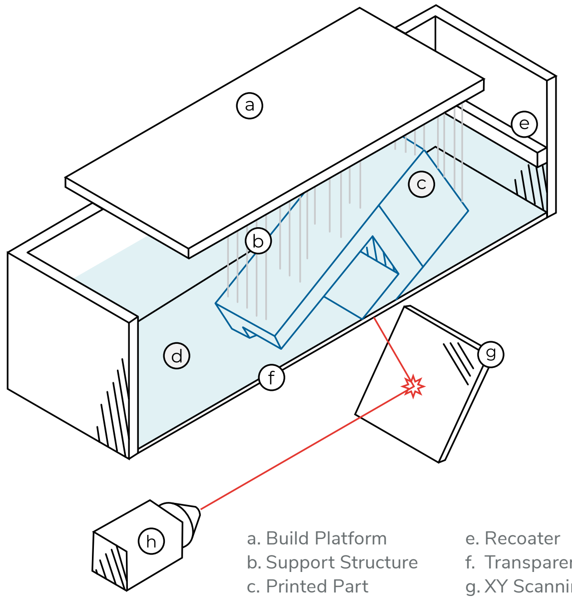
VAT PHOTO-POLYMERIZATION



a. Build Platform
b. Support Structure
c. Printed Part
d. Liquid Photopolymer
e. Recoater
f. Transparent Screen
g. XY Scanning Mirror
h. UV Laser

Vat photopolymerization uses liquid rather than powder or filament. Printing techniques vary, but they all use photopolymer resins – often tough, transparent and castable materials. The resins are cured using UV light directed across the surface of the resin.

Stereolithography (SLA) – This method has its roots in the first 3D printers. SLA uses a build platform in a tank of liquid polymer. A UV laser shines from beneath the object and maps each layer. When finished the platform rises and liquid resin pools below the object to begin the next layer.

Direct Light Processing (DLP) creates each layer of an object by projecting laser light on tiny mirrors, resulting in the projection of square pixels, layer-by-layer. It is often faster than SLA because each layer is fully projected in a single operation.

APPLICATIONS

Vat photopolymerization produces parts with extreme detail and smooth surfaces. The process is a good fit for jewelry, the medical industry, and low-run injection molds.

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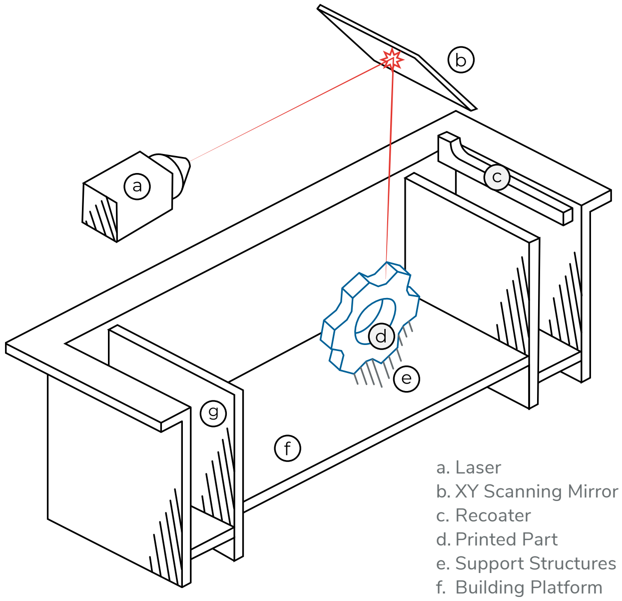
POWDER BED FUSION



a. Laser
b. XY Scanning Mirror
c. Recoater
d. Printed Part
e. Support Structures
f. Building Platform
g. Overflow Bin

As the name suggests, Powder Bed Fusion (PBF) involves melting particles to fuse them together. Particles of plastic or metal powder are either “sintered” (partially melted) or fully melted using thermal energy in the form of a laser, beams of electrons, or a heated print head.

A ultrathin layer of material is spread by a roller or blade over the preceding layer on a print bed or build plate. The powder is fed onto a build platform that lowers to accommodate each consecutive layer of powder. Excess powder is removed at the end of the additive process.

Common powder bed fusion processes are – direct metal laser melting, electron beam melting, directed metal laser sintering, selective laser melting, selective laser sintering, and selective heat sintering.

APPLICATIONS

Powder bed fusion is an ideal solution for many types of manufacturing because it’s easy to design for and allows users to build complex geometries. Parts typically possess high strength and stiffness with a large range of post-processing methods available.

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TAKING GUESSWORK OUT OF DMLS (DIRECT METAL LASER SINTERING)

CHALLENGE

Support structures form the basis for the AM part foundation, provide structural support, are critical in eliminating warp, and improving heat extraction generated from the laser sintering.

With direct metal laser sintering (DMLS), surface temperature gradients and shrinkage can lead to stress and distortion. The goal was to develop a modeling tool that would determine optimal part orientation and support location.

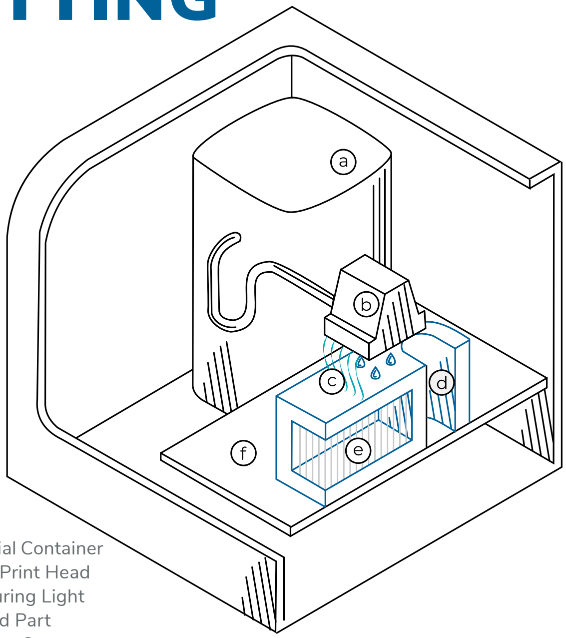
SOLUTION

In-depth research was conducted to learn how engineers handle these issues. This greater understanding of the rules used to select an optimal part orientation were then codified to automatically generate an optimal part orientation. Work was also done to develop a support minimization function and create a heat transfer model for DMLS allowing a prediction of thermal mass and temperature gradients to generate a minimal part distortion model.

The R&D was compiled into an AutoCAD Inventor™ plug-in called ATLAS. Subsequently Atlas 3D was established and the ATLAS software has been commercialized as Sunata™, a web-based solution that answers the orientation and support structure question. Upload a design file and Sunata™ models the part in 100 different orientations to arrive at the optimal orientation and associated support structures. Atlas 3D has also expanded Sunata’s™ capabilities to include distortion mapping, build cost estimates, parts nesting, and more.

Atlas 3D
atlas3d.xyz

MATERIAL JETTING



a. Material Container
b. Inkjet Print Head
c. UV Curing Light
d. Printed Part
e. Support Structure
f. Building Platform

Material Jetting is an AM process that uses drop-on-demand (DOD) technology. Like a 2D inkjet printer, tiny nozzles dispense tiny droplets of a waxy photopolymer, layer by layer. UV light cures and hardens the droplets before the next layer is created. This additive technology heavily relies on support structures, so a second series of nozzles dispenses a dissolvable polymer that supports the object as it is printed. When the printing is complete, the support material is dissolved away. Material jetting is one of the most precise AM processes and can print layers as thin as 15-16 microns.

Nanoparticle Jetting (NPJ) is a sub-category of material jetting that uses liquids infused with metal particles. As each layer of droplets is deposited onto the print bed, the heated build chamber cause the liquid to evaporate, leaving a layer of metal.

APPLICATIONS

Ideal for realistic prototypes with high detail, high accuracy, and smooth finishes. Material jetting allows for multiple colors and materials in a single print.

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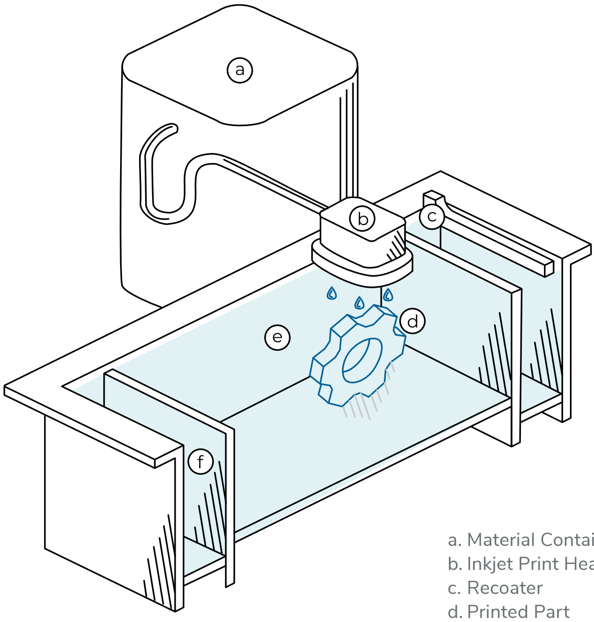
BINDER JETTING



a. Material Container
b. Inkjet Print Head
c. Recoater
d. Printed Part
e. Powder Bed
f. Overflow Bin

The Binder Jetting Process is similar to material jetting, but uses powdered material and a binding agent. Nozzles deposit tiny droplets of a binder on an ultrafine layer of a broad range of powdered materials (metal, ceramic, glass, etc.). Multiple layers result from the powder bed moving downward after each layer is created.

The finished "print" is in a green state and requires post-processing. Bronze may be used to infiltrate a metal object to improve its mechanical properties enough to make it a functional component. A cyanoacrylate adhesive is a common infiltrant for ceramic. Ceramic objects produced by binder jetting are still brittle and are primarily used as architectural models or models for sand casting.

APPLICATIONS

Ideal for aesthetic applications like architectural and furniture design models. Not very functional because of its brittle nature.

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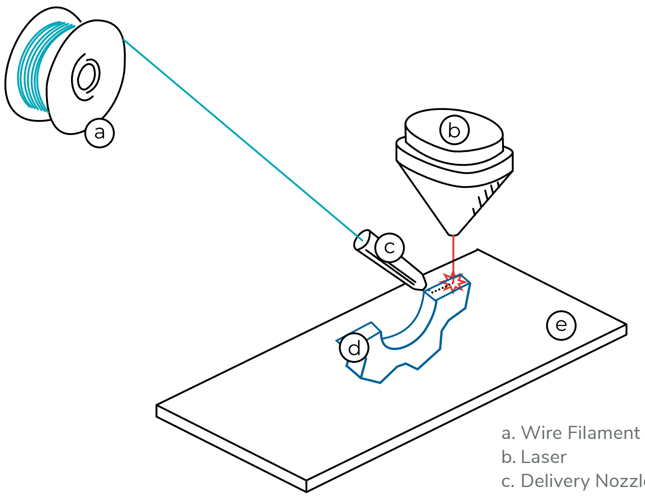
DIRECTED ENERGY DEPOSITION



a. Wire Filament
b. Laser
c. Delivery Nozzle
d. Printed Part
e. Build Platform

Directed Energy Deposition (DED) uses highly focused thermal energy (laser, electron beam, or plasma arc) to melt and fuse material jetted into the heated chamber from either powdered metal or wire filament. DED closely resembles welding and is commonly used to repair and maintain existing parts, although it can be used to deposit material directly onto a build tray.

This AM process is most commonly used with metal, although some systems can use ceramic powder or polymers. DED is the fastest AM technology, does not require support structures, and is perfect to build large parts that don't need tight tolerances. The metal material is also melted before it cools and hardens, this means parts are fully dense and production ready although the surface finish is poor. Most DED parts require significant secondary machining.

APPLICATIONS

This process is ideal for repairing or adding material to existing components. DED can also be used to build objects very quickly with the size and complexity only limited by robotic arm reach and axes.

INDUSTRY LEADERS

OPTOMEC SCIAKY INC

AMERICA MAKES AND ITAMCO: NEXT-LEVEL DED MACHINES

CHALLENGE

The main purpose of this America Makes project was to commercialize the technology for next-generation DED metal AM machines.

This technology would allow the industrial user base to take advantage of the lower cost and increased flexibility of scalable, multi-axis (9 and above) robot systems in AM. The project built on existing CAD-to-path AM robotic software with the goal of a commercial release along with a multi-process, multi-meter, multi-material production-ready, robot-based 3DP system.

SOLUTION

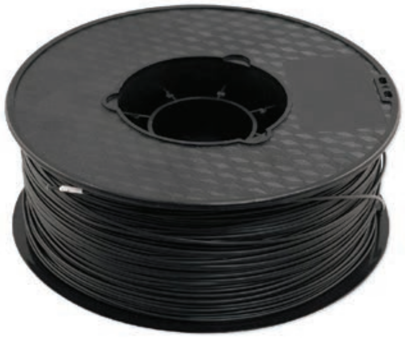
ITAMCO and other members constructed a demo system to test and refine robotic 3DP hardware and software through the printing of team member parts. This effort leveraged existing Wolf Robotics proprietary CAD-to-Part printing tools to enable multi-axis, multi process laser hot wire and blown powder printing. Software was developed to allow a CAD model to be broken into sections that can be assigned to different processes, materials, and/or robots within a robot cluster as part of a "build strategy" defined for a specific part by the software user.

One robot was used for printing on the project; however, the project team investigated multi-robot coordination strategies to serve as a foundation for potential future projects related to multi-robot printing that addresses robot reach and collision avoidance.

America Makes
americamakes.us

MATERIALS TYPES

Specific AM processes and machines dictate the materials that can be used, and each process is compatible with multiple materials. Most popular are plastics and metals, and composites and ceramics can also be printed. Below are some of the most common materials:



PLASTICS

Plastics are suitable for both prototyping and some functional designs. They are grouped into thermoplastics (melt at a certain temperature) or thermosets (permanently rigid when heated). Thermoplastics are better suited for functional applications, while thermosets are best known for quality appearance.

PLA

The most common, low-cost, low heat AM plastic. Best suited for non-functional prototypes with sharp and precise details.

ABS

Excellent impact resistance and used for many applications. Better mechanical and thermal properties than PLA.

RESIN

Produces high-detail parts. This thermoset polymer is ideal for detailed prototyping.

NYLON

Great for functional applications with high chemical and abrasion resistance and excellent mechanical properties.

PEI (ULTEM)

Engineering thermoplastic with good mechanical properties. Exceptional chemical and flame resistance.

TPU

Thermoplastic elastomer with low hardness and rubber-like feel. Can be easily flexed and compressed.

ASA

Better printability than ABS. Resists weather, color fade, UV, and chemicals. Used for outdoor and automobile applications.

METALS

Metals are used when high strength, hardness, or thermal resistance are required in AM. When printing in metal, topology optimization is critical to maximize part performance and mitigate the high cost of the technology.

DMLS/SLM are compatible with the largest range of metals and produces parts for high-end applications. For less demanding metal use-cases, Binder Jetting is a lower cost option. Extrusion based metal AM systems (similar to FDM) are being released and are expected to drive down the costs of metal AM for prototyping.

STAINLESS STEEL

Multiple types of stainless steel powders can be used in AM. These metal alloys are highly ductile, wear and corrosion resistant, and are easily welded, machined and polished.

ALUMINUM

Good strength-to-weight ratio, high thermal and electrical conductivity, low density and natural weather resistance.

TITANIUM

Excellent strength-to-weight ratio, low thermal expansion, and high corrosion resistance. Sterilizable and biocompatible.

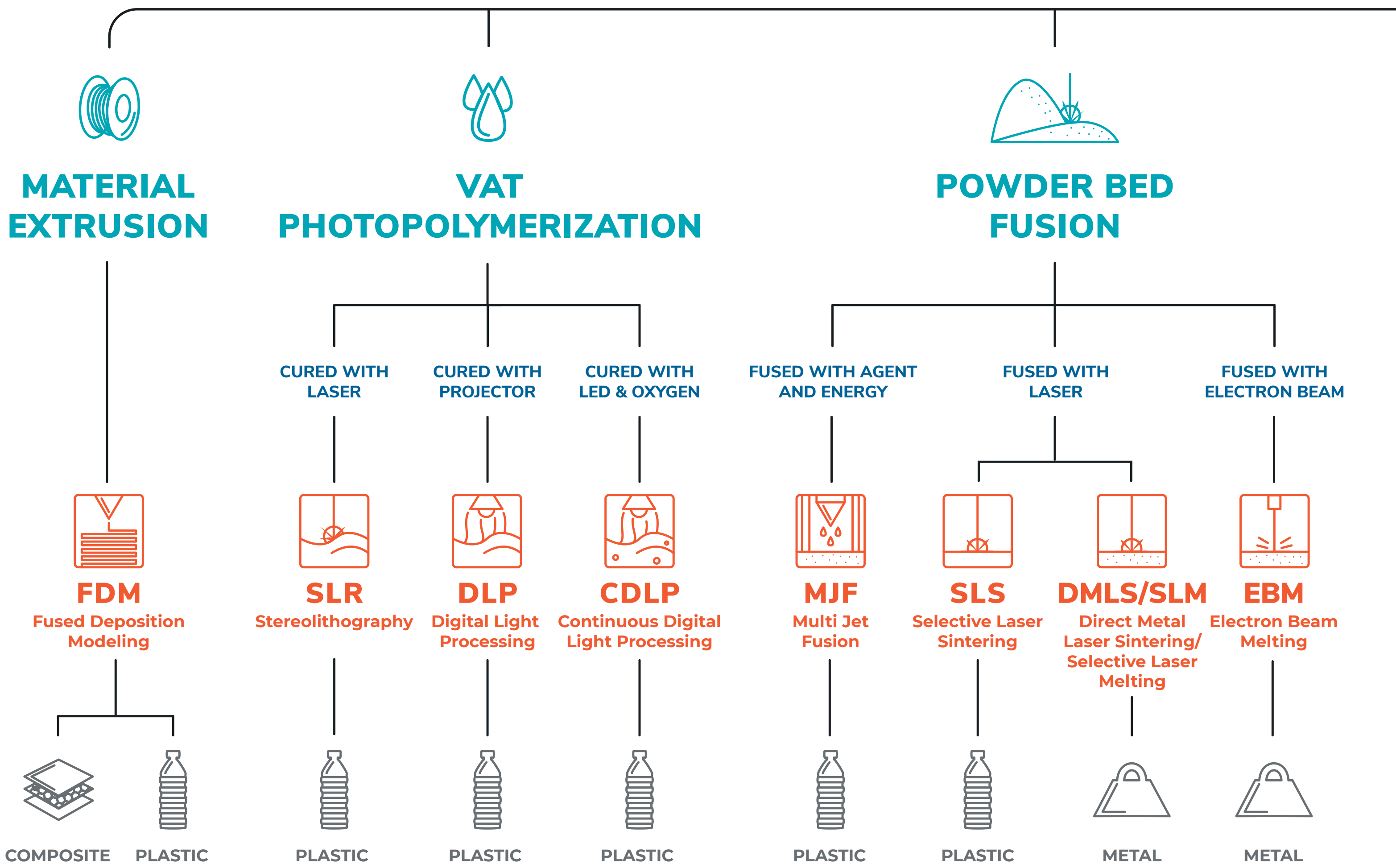
COBALT-CHROME

Metal super-alloy with excellent strength and outstanding corrosion, wear and temperature resistance.

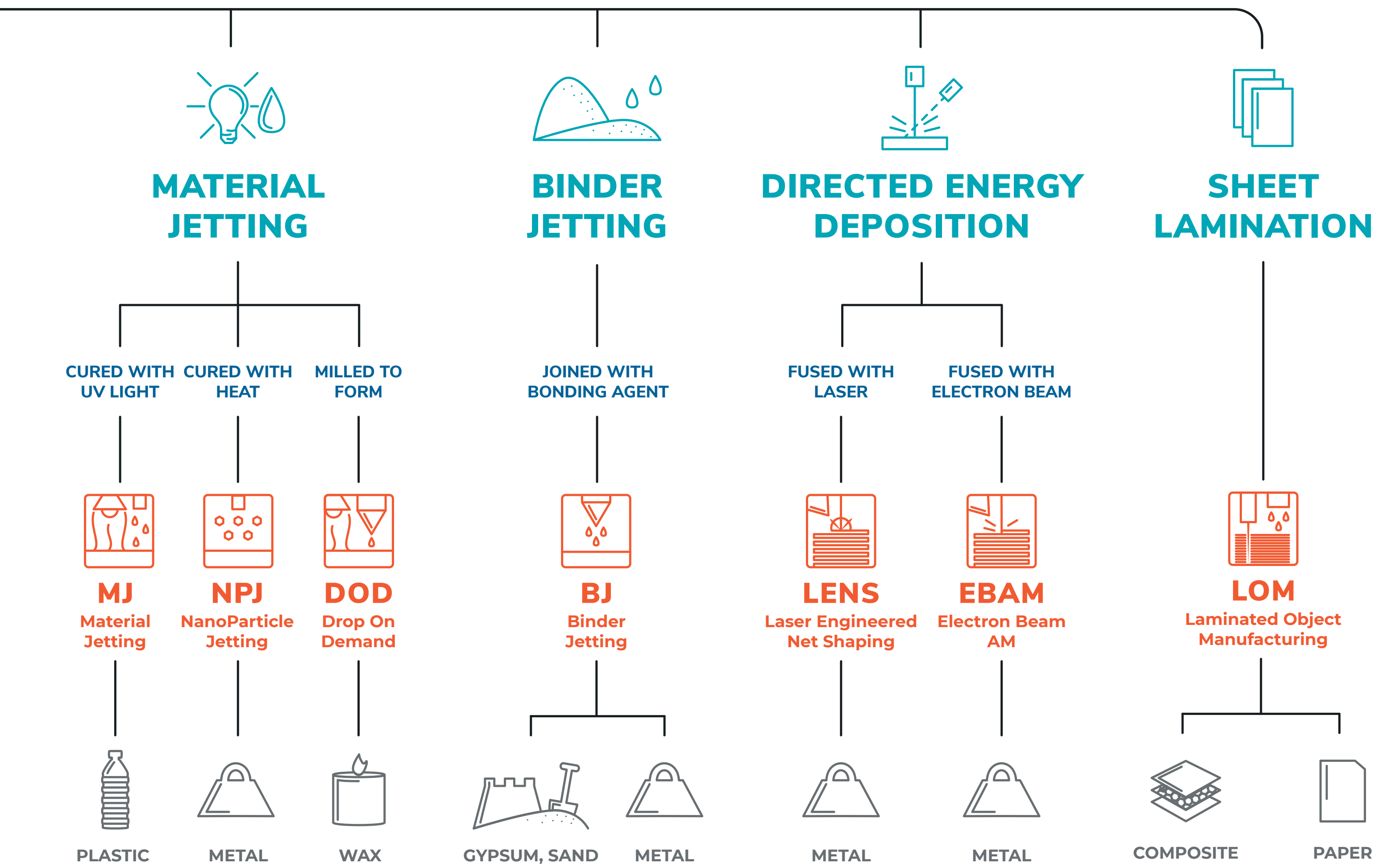
NICKEL ALLOYS

Excellent strength and fatigue resistance. Can be effectively used at extreme temperatures.

ADDITIVE MANUFAC



TURING PROCESSES



BENEFITS

Compared with traditional manufacturing methods, AM offers enormous benefits, including less tooling, less CNC machining, and minimal assembly. AM has enormous potential to completely change the way products are designed, built, distributed, sold, and serviced.

AM adoption is highest in industries where the higher production costs outweigh the value AM can generate. Engineering-focused industries such as aerospace, automotive, and medical can accelerate prototyping. Completely new design features can be explored, or fully custom products can be easily created. The ability to create topology optimized structures with high strength-to-weight ratios are particularly appealing.

High-value/lower-volume companies benefit from AM's more flexible manufacturing processes, less material waste, shortened assembly times, and the ability to create materials with completely new properties. Spare-parts manufacturers such as maintenance, repair, and overhaul are freed from parts ever becoming obsolete, have faster time to market, more local and on-demand production opportunities, and independence from traditional suppliers.

LIMITATIONS

Despite all of the optimism about AM, there are still major challenges to overcome before the technology is widely adopted.

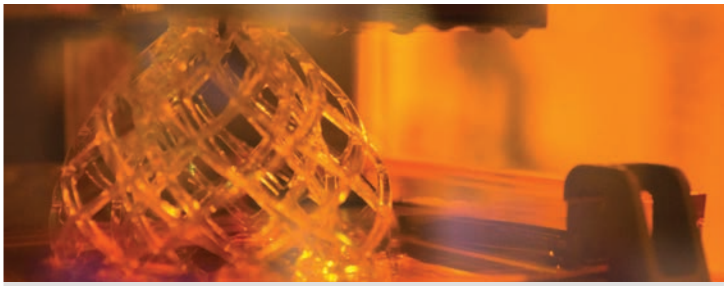
SIGNIFICANT SKILLS GAP – Capturing the technology's full potential often means rethinking the way products are designed. AM allows nearly complete freedom for the designer. Product designs can be specifically calibrated to enhance specific properties, part orientation must be taken into consideration, and support structures must be incorporated.

HIGH PRODUCTION COST – High cost is a major barrier to more widespread adoption. AM avoids the high up-front tooling costs, but advantages tend to fade as the volume of production increases. Although with plastics the volume threshold where AM has an advantage is increasing. At low volumes metal AM often remains much more expensive than traditional methods because of high material costs, slow build-up rates, long machine running hours, and post-processing costs.

LIMITED PRODUCTION SCALE – Most current AM machines are made for prototyping rather than serial production. Mass production is difficult to attain, and scaling for mass production is nearly impossible for most products and components.

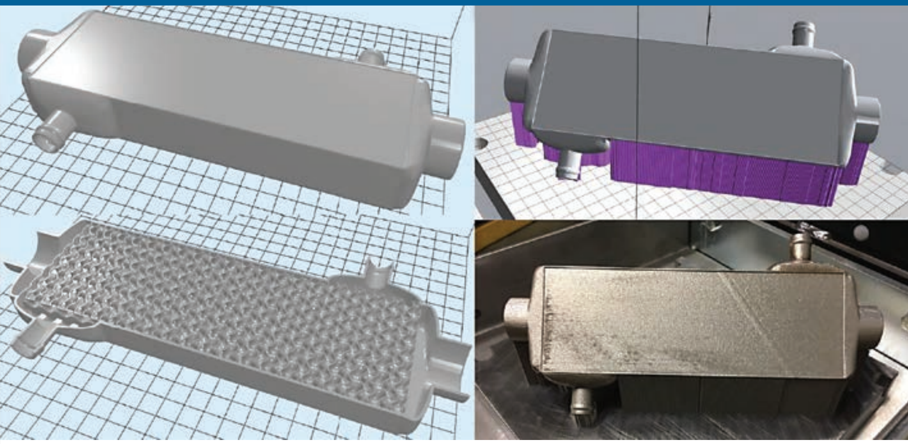
KEY BENEFITS OF AM

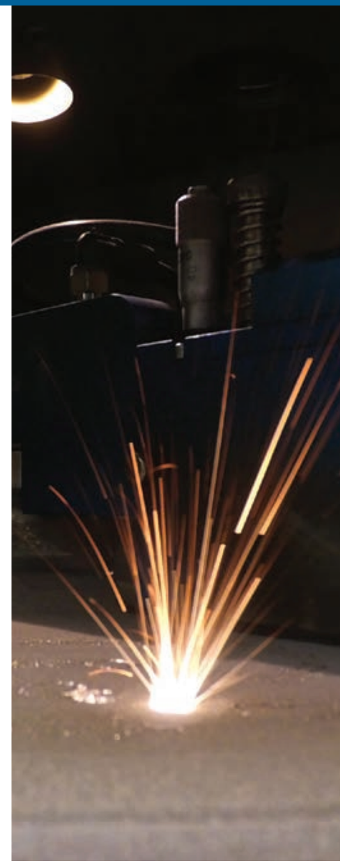
1. **Improved product functionality**
2. **Easily created complex parts**
3. **More efficient production**
4. **Customization**
5. **Shorter time to market**
6. **Minimal lead time**
7. **Less waste**
8. **Reduced obsolescence**
9. **Quicker iterations**
10. **Ever expanding material types**



KEY LIMITATIONS OF AM

1. **Skills gaps**
2. **Expensive production costs**
3. **Limited production scale**
4. **High material costs**
5. **Slow build-up rates**
6. **Prototype-centric**
7. **Limited accuracy and tolerances**
8. **Removal of supports/post processing**
9. **Wrong tool for the job**
10. **Limited material variety**



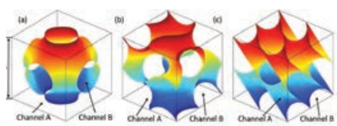


NEXT GENERATION HEAT EXCHANGERS

ITAMCO was asked to create a more efficient, metal heat exchanger for a large OEM. Triply periodic minimal surfaces (TPMS) were investigated and incorporated into the heat exchanger. TPMSs are surfaces of zero mean curvature, meaning that the sum of the principal curvatures at each point is zero. These surfaces minimize its area in a fixed boundary curve, and have huge potential for dissipating heat.

WHY TPMS?

TPMSs unique features for next-generation heat exchanger design:

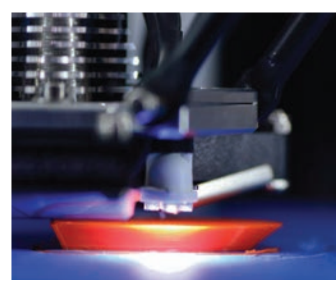


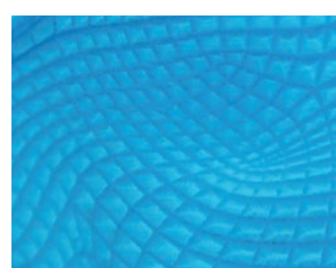
1. TPMSs divide a 3D domain into two separated but interpenetrating channels which provide a large surface area to volume ratio. Two flows with different temperatures can pass through the channels and exchange heat efficiently.
2. All channels are inter-connected in all directions. This means the flow is free to move in any direction and the hydrodynamic resistance and pressure drop is low.
3. TPMSs create complex flow patterns which will enhance heat transfer efficiency and prevent fouling.
4. AM TPMS Heat Exchangers (TPMS-HX) are printed as a single piece without welding or brazing.
5. TPMSs have high structural integrity and the support removal process can be avoided.

CREATING AM TPMS HEAT EXCHANGERS

A gyroid TPMS was designed with a wall thickness of 1mm for the core of the TPMS-HX. Boundary walls, inlets, and outlets were added to the TPMS-HX to separate the hot and cold fluid.

The TPMS-HX design was imported into Atlas3D's® Sunata™ software to find a proper build orientation and generate the necessary support structures. The oriented STL and support files were downloaded from Sunata™ and imported to EOSPRINT. ITAMCO's EOS M290 machine was used to successfully build the TPMS-HX using metal powder feedstock 17-4PH stainless steel.





APPLICATIONS

TRANSPORTATION

While still in its infancy in this sector, AM is beginning to revolutionize transportation. Aerospace, automotive, and maritime sectors are looking at the technology to cut R&D time and expense and build specialized components. In aerospace, where material costs can be extremely expensive, AM offers a new way to create better results than typical manufacturing. AM can be used to create lighter, stronger, and more resilient components.

CONSUMER PRODUCTS

Consumer product manufacturers have embraced 3D printing to help iterate and adjust designs faster. Simulating the look and feel of the final product during design reviews can help prove viability to stakeholders. AM is also used in producing detailed consumer electronics early in the product development life cycle with realistic aesthetics and functionality. The entertainment industry has adopted AM for props, costumes, sets, and finely detailed models.

MEDICAL

AM has had a massive impact on the medical industry, and is widely used in the prosthetic industry, functional prototypes, anatomical models, dental implants and surgical grade components. Material development is key in the medical industry and more validation of biocompatible materials and the methods used to produce parts could open the door for even more customized implants, life-saving devices, and tools that increase positive patient outcomes.

ARCHITECTURE

Many architectural firms have discovered the potential of AM for the construction of models. It is possible to build very detailed structures using the technology. The number of architecture firms using this technology is growing rapidly. AM has also been used in the actual construction of buildings and structures. In 2017 the first 3D printed house was built, and since then AM has been used in bridge building and shows potential for continued growth.

ENERGY

Success in the energy sector relies on the ability to quickly develop custom, mission-critical components that can withstand extreme conditions. AM can now produce the efficient, on-demand, and lightweight components the energy sector requires. Applications include rotors, stators, turbine nozzles, down-hole tool components, detailed models, fluid/water flow analysis, flow meter parts, pressure gauge components, control-valves, and pumps.

OTHER

Additive manufacturing is used in many other sectors. AM facilitates creation and personalization in a way traditional manufacturing does not. The technology makes it possible to overcome obstacles, complexities, and offers more solutions to problems. As AM becomes democratized and accessible, dramatic increases in applications, speed, and use-cases will drive innovation globally and even more industries may turn to AM for large volume demands.

ADDITIVE MANUFACTURING
VERSUS
TRADITIONAL MANUFACTURING

AM is exceptional at manufacturing custom parts and prototyping. Its unique characteristics leave it best suited for specific circumstances. When choosing between additive (AM), subtractive (CNC machining), or formative (injection molding) manufacturing technology use these few simple guidelines to aid in the decision making process.

RULE OF THUMB: Additive Manufacturing is the best option when prototyping or a single or limited production of parts is required quickly at a relatively low-cost. It is also the right choice when part geometry cannot be produced with any other manufacturing method.

SUBTRACTIVE TECHNOLOGY (CNC MACHINING) MAKES MORE SENSE WHEN:

- **Medium to Large Volumes:** CNC machining is typically more cost-effective for parts in the 100’s where the economies of scale start to kick in.
- **Simple Geometries:** If a design can be easily created through a subtractive process then CNC machining is the best option. This is especially true for metal parts.
- **High Material Requirements:** Where stringent mechanical properties are required, testing should be performed. AM printed components typically have lower strength properties compared to machined bar or a forging. However, AM is rapidly gaining momentum and is starting to equal traditional methods in some cases (search the Internet for “Additive Manufactured Parts Outperform 17-4 PH Stainless Steel,” for an example).
- **Dimensional Accuracy:** For parts requiring tight tolerances, traditional CNC machining is best. For complex geometries, a hybrid approach of printing first and then CNC machining afterwards is also an option.

THE FUTURE OF ADDITIVE MANUFACTURING

AM limitations are systematically being overcome by a growing AM design services industry, government-funded research and development, and specialized consulting firms. Analysts believe next generation AM machines will slash current production time and costs as more patents expire, post-processing needs decrease, and manufacturers leverage increased economies of scale. AM’s future lies in its ability to reduce production costs while expanding its capacity for industrial production.

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