ADDITIVE MANUFACTURING
A MANUFACTURING INNOVATION WHOSE TIME HAS COME

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ABSTRACT

One of the newest areas of interest for American manufacturing is the rise of additive manufacturing, or 3-D printing. It has the potential to revolutionize the ways component parts and finished assemblies are produced. This paper provides an overview of the subject.

Introduction

In the middle of 2012, the United States Government launched an initiative they hope will invigorate the resurrection of the manufacturing industry in the U.S.

> *"In August 2012, the National Additive Manufacturing Innovation Institute NAMII was formally established in Youngstown, Ohio, as the pilot institute under the National Network for Manufacturing Innovation (NNMI) infrastructure. Driven by the National Center for Defense Manufacturing and Machining (NCDMM), NAMII serves as a nationally recognized additive manufacturing center of innovation excellence, working to transform the U.S. manufacturing sector and yield significant advancements throughout industry.*
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> *In March 2012, President Obama announced his plans to revitalize the U.S. manufacturing base with the creation of the National Network for Manufacturing Innovation (NNMI). At the core of the NNMI will be as many as 15 institutes for manufacturing innovation throughout the country. The initial step in building this collaborative infrastructure required the creation of a pilot institute to serve as a prototype for subsequent NNMI institutes.*
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> *An inter-agency advisory council of technical experts from the Department of Defense (DoD), Department of Energy (DOE), National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), and the Department of Commerce's National Institute of Standards and Technology (NIST) determined the pilot institute's focus to be additive manufacturing.*
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> *A Broad Agency Announcement was issued in May 2012, officially commencing the solicitation of proposals to identify an agency or consortium of agencies capable of operating the pilot institute with a forward-looking technical vision; previous collaborative research experience; a background in educational outreach and workforce development; and the leadership to sustain the institute.*
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> *Upon completing its review of submitted proposals, the advisory council selected the National Center for Defense Manufacturing and Machining (NCDMM) to manage the National Additive Manufacturing Innovation Institute (NAMII), the NNMI pilot institute. The official announcement of the award came on August 16, 2012 at NCDMM's Youngstown, Ohio facility and the headquarters of NAMII." http://namii.org/*

Why is the U.S. Government interested in investing money in a "Rust Bowl" community like Youngstown, Ohio? Especially in a manufacturing facility? Have the people in Congress lost their minds or is this an example of another pork barrel project gone radically wrong? Perhaps not!

Does the term "additive manufacturing" mean anything to you or your business? If it doesn't, make a note of it, because it may be either a threat or an opportunity in the near future. Many are viewing additive manufacturing as a new wave of manufacturing that will revolutionize the ways things (at least some things) are made. It gets its name because parts are produced by using a printer to add layer after layer of materials onto a surface to form a three-dimensional object. It is like making a layer cake in the kitchen except the additive manufacturing layers are much thinner (upwards of 2000 per inch) and much more stable when finished.

There are numerous videos that illustrate the way in which the additive manufacturing process works and the products that can be made with it.

> 3-D Printing http://www.industryweek.com/technology/will-3d-printing-change-world?NL=IW-02&Issue=IW-02_20130308_IW-02_736&YM_RID=crandllre@appstate.edu&YM_MID=1378187&sfvc4enews=42
>
> Mayo Clinic and hip replacement http://www.textually.org/3DPrinting/cat_printing_prosthetics.html
>
> Oak Ridge and Artificial Limb http://www.3ders.org/articles/20120809-3d-printed-lightweight-robotic-hand-wins-2012-RD-100.html
>
> Video about building a bicycle out of 3-D parts http://www.youtube.com/watch?v=hmxjLpu2BvY&feature=player_embedded

Is there interest in additive manufacturing among both practitioners and academics? Figure 1 shows the number of articles published about "additive manufacturing" or "3-D printing" through the end of 2012. As the figure shows, the number of articles about additive manufacturing, or 3-D printing, has increased dramatically during the past few years. There is no indication that the interest is abating. Although the number of articles in trade publications lead those in academic journals, this is typical for the early stages of a new management program. The level of activity indicates that additive manufacturing is of great interest to both groups.

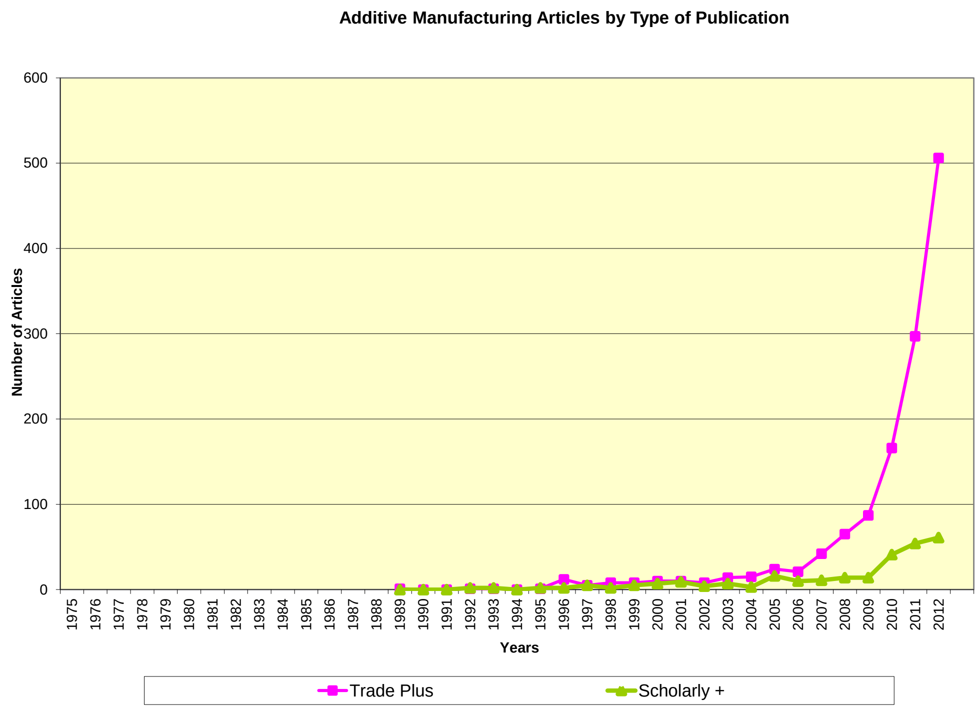

Figure 1. Number of Articles about Additive Manufacturing

The Additive Manufacturing Process

This process is also known as 3-D printing. In a comprehensive article on the subject, Berman (2012) explains that 3-D printers seamlessly integrate with CAD software, which directs the printer operation to deposit layers of materials to form the desired object. While still in its early stages of development, additive manufacturing has many researchers and practitioners actively seeking ways to improve and extend the applications of this process.

In explaining the progression among descriptive terms such as 3-D printing and rapid prototyping, Terry Wohlers, one of the pioneers in the additive manufacturing movement, explains:

"Old habits die slowly. Case in point: Transitioning to the term "additive manufacturing." That's now the official name of what some refer to as rapid prototyping, freeform fabrication, and a host of other names. Additive manufacturing is the official name …. according to ASTM International F42 Committee on Additive Manufacturing Technologies. The group put a lot of thought into it, first selecting AM as the favorite for the name of the committee. It then carefully defined it… The definition includes all applications of the technology, including the making of models, patterns, and prototypes for form, fit, and function; mold, die, fixture, and assembly tooling; and custom and limited-edition products, replacement parts, and short-run and series production. Rapid prototyping is the most popular application of AM technology, but it is only one of many." (Wohlers 2010)

Gibson, Rosen and Stucker (2009) report that most AM processes involve the following eight steps:

1. Build the CAD software model to describe the external geometry
2. Convert the CAD file to the STL file format (the de facto standard)

3. Transfer the STL file to the AM machine (size, position and orientation for building)
4. Set up the AM machine (material constraints, energy source, layer thickness, timing)
5. Build the part (usually an automated process requiring only superficial monitoring)
6. Remove the part (assure there are no moving parts or high temperatures)
7. Post processing (cleaning, support removal)
8. Application (may require additional treatment such as painting or assembly with other parts)

While the basic idea behind AM is to deposit layer upon layer of material to form a finished part, there are several processes that do this. Diegel (2010) describes the process as follows: “The main technologies that can, today, be classified as rapid manufacturing technologies (as opposed to rapid prototyping) are Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM). He goes on to explain that a layer of material is deposited and then fused to the specified surface with either a laser beam (SLS and SLM) or an electron beam (EBM). The unfused material acts as support material for all the layers above it and is removed once the part is complete. See Wikipedia (2012) for a more extensive list of 3-D printing processes.

History of additive manufacturing

The first use of additive manufacturing (AM) was to make prototypes, and was known at that time as rapid model prototyping (RMP). Prototypes could be made by using a CAD design that was loaded into a printer. It was also called 3-D printing for obvious reasons. This approach made it possible to produce complex shapes that would have taken much longer to design and product through conventional methods, such as molding and machining.

Once 3-D printing became more commonplace, pioneers began to use it to make small lots of production parts. Although it is slow (relative to numeric-controlled machines) in making a part, it requires much less time in the design and setup times. Consequently, making small quantities of parts is economical with the additive manufacturing process. The AM process is also capable of making complex designs that would be difficult, if not impossible, to make with conventional methods. It was during this period of expanded application that the designation changed from rapid model prototyping to additive manufacturing, a contrast to subtractive manufacturing where material is machined away in order to reach the desired part. Some applications of model building include bicycle chains, gear boxes and even miniature sculptures of famous people.

Applications

As application opportunities increased, users became more innovative in their applications. Some current applications include replacement parts for washing machines, food processors and small gears (Berman 2012). An industry that is especially interested is the aircraft industry where lighter weight is a treasured goal. Boeing has 200 different AM part numbers on 10 production platforms, including both military and commercial jets (Wohlers 2012). Another application involves a joint project between Stratasys, Inc. and Optomec, Inc. to produce a “smart wing” for an unmanned aerial vehicle (UAV) model with functional electronics (Close-Up Media, Inc. 2012)

In the automotive industry, General Motors (GM) has been using AM for the past 20 years. In a lab with 15 specialists and 18 machines, they crank out some 20,000 unique parts a year, including bumpers, grilles, spoilers, and mirrors. They also can build prototypes of engines, transmissions, brake lines and drive shafts (Fish 2011). Daimler is another automotive company that is using additive manufacturing for making aluminum alloys that are the foundation for lightweight automobile construction (Brooks 2012)

Do-it-yourself enthusiasts are also looking at the possibility of using 3-D printers to make craft items, jewelry and other small parts. However, Whitman (2012) cautions that 3-D printing won't be for the average homeowner. However, printer manufacturers continue to drive the cost of low-end printers down. Some are now available in the $1,000 to $2,000 range (Seitz 2012)

The medical field is also using additive manufacturing for making hearing aid molds, dental crowns, and prosthetic limbs, such as knees and arms (Berman 2012). See the video by David Goldman, CNN Money (2012). Wohler (2012) reports that millions of hearing aids and dental copings are produced annually because AM can produce products that are unique in size and shape. Although the industry is heavily regulated, implant manufacturers in the US were approved by the US Food and Drug Administration to manufacture certain products using electron beam melting (EBM) in 2010 (Wohlers 2011).

One of the areas in which AM can be used in is training students in STEM (science, technology, engineering and math) practices. The National Science Foundation has funded two Advanced Technological Education centers – MatEd (the National Resource Center for Materials Technician Education) and RapidTEch (the National Center for Rapid Technologies) to develop new AM competencies and curriculum. The project is designed to accelerate AM skills development by "decreasing the time-lag between global AM Standards development, their translation into core competencies, active integration into curriculum, and their delivery in the classroom." (Fridan 2011) If the United States is to meet its future challenges, it must train more students to pursue engineering and other STEM careers. Students who like the hands-on experience of making things will become excited about AM education opportunities (Lacey 2010).

One outgrowth of AM is the possible application of the technique to buildings. Behrokh Khoshnevis, a professor of industrial and systems engineering at the University of Southern California in Los Angeles, has spent 15 years working on the idea of using AM techniques to construct buildings. He believes they could be built at lower cost and the technique could be used to build emergency housing in case of disasters (Thilmany 2010).

AM is finding application in the fashion industry. Shoes, clothing and accessories made by AM have been featured at large fashion shows. Models at the Stockholm Fashion Show wore shoes manufactured in polyamide by laser sintering (LS) methods (Wohlers 2011). In order to keep up with market changes, New Balance Shoes uses AM to design new products rapidly (Hessman 2012)

In one of the more exotic potential applications, NASA is planning to bring a 3D printer to the space station by 2014 to make replacement parts and tools. With the help of Autodesk, they have already printed a wrench in zero gravity conditions (King 2012). NASA has already used AM by building 70 parts for the Mars Rover, using a production-grade Stratasys 3D printer with its patented Fused Deposition Modeling (FDM) technology (Plastics Technology 2012).

Looking even further into the future, one of the most optimistic researchers envisioned the convergence of three distinct research areas: rapid prototyping (AM), smart polymers, and cell adhesion could eventually result in what could be called organ manufacturing, or making body parts. He speculates that "Once we learn how to produce isolated body parts, we could eventually be able to build a whole body." (Mironov 2003)

Benefits

Some of the benefits of additive manufacturing include:

- Using 3D printing can eliminate the need to make custom tooling which reduces the time to develop new product models for evaluation (Hessman 2012).
- AM has the capability to make complex parts that would be difficult, if not impossible, with conventional casting and machining techniques. "Almost, without exception, if a part can be modeled on a computer in 3-D, it can be sliced and printed, layer by layer, on an AM system." (Wohlers 2012) Parts can include lattice structures and honeycomb features.
- Lower weights of finished products. AM has found application in building unmanned aerial vehicles (UAVs) and aircraft parts where the build time is faster and the lighter weight reduces fuel consumption (Wohlers 2012).
- The materials used are powders. It is possible to reduce the number of processes necessary to prepare the materials for use, such as making the aluminum into billets. This results in a leaner and greener supply chain (Hargreaves 2011)
- High yield (low waste). The process can use almost all of the powdered materials it starts with. This compares favorably with the subtractive processes that may machine away over half of the material they start with (Velocci 2012).
- Topology optimization. This is a technique that helps decide where to locate the material in a part to optimize the strength-to-weight ratio. (Wohlers 2012)
- Predictability of product reliability. Whether the AM process uses a laser or an electron beam, it is possible to model the time/temperature profile at any location of a component. With that information, the product reliability can be accurately predicted (Velocci 2012)
- Reduction in component count. AM does not have the geometric limitations imposed on molds and dies; therefore, what would require multiple parts in conventional processing can be built in one part design (Wohlers 2011).

Obstacles

Because of the newness of the AM technology, researchers and users are working their way through the learning curve to determine the best combination of materials and processes to produce an increasing variety of products. Some of the most often cited shortcomings of AM are:

- AM has a slow manufacture time, when compared to numerical control machines that have been programmed to produce high volumes of the same part.
- Some of the products have weak bonding between layers that can lead to delamination and breakage under stress (Berman 2012)
- There may be a need for some conventional finishing operations because of the ridges formed by the layer depositions.
- Limited materials can be used. However, some of the most popular metals in use include the titanium alloy Ti-6Al-4V, cobalt-chrome, stainless steels, tool steels, aluminums such as AlSi10Mg and 6061T6, jewelry and dental gold alloys, and nickel-based superalloys such as Inconel 625 and 71B (Wohlers 2012)

Progress is being made to reduce or eliminate these obstacles in the development of AM applications.

Companies

There are a number of companies in the AM field. To date, many of them are still relatively small, although they may be growing rapidly. We will briefly describe two of the more prominent companies devoted exclusively to AM applications – Stratasys, Inc. and 3D Printing. We will also mention two large global companies that have made serious efforts in AM – General Electric (GE) and Hewlett-Packard (HP).

Stratasys, Inc. invented Fused Deposition Modeling (FDM) and has applications in a number of industries, including aerospace, automotive, commercial, consumer, education, medical and military (http://www.stratasys.com/Resources/Information-Center.aspx). It is one of two prominent manufacturers in the AM field. They have recently merged with Objet, an Israel company, to form a powerhouse company with a market valuation of $3 billion, with a full line of machines to make an almost unlimited array of products (Hessman 2013)

3D Systems was founded in 1986 by Charles Hull who developed the stereolithography (SLA) process and operates out of Rock Hill, South Carolina (Juster 1994). They have applications in transportation, energy, consumer, recreation, healthcare and education industries (http://www.3dsystems.com/).

Two major companies – General Electric (GE) and Hewlett-Packard (HP) already have positions in 3D printing. HP will probably build on their base printer business, although their thinking has not been revealed. It recently ended its relationship with Stratasys, which had been making HP's exclusive line of printers since 2010, mostly marketed in Europe (Gupta 2012). This may mean they are going to focus on internal developments.

GE reports its scientists already are studying additive manufacturing techniques to reduce the labor and production costs of ultrasound systems, continuing GE's increasing emphasis in the healthcare field. (Health and Beauty Close-Up 2011). GE Aviation is also researching the use of AM to reduce the weight of jet engines (Zelenski 2012)

Conclusions

Additive manufacturing is a proven technology and holds promise for invigorating the manufacturing industry in the United States. To provide greater impetus to the research, the Department of Defense and the Department of Commerce has awarded $30 million to a consortium of regional businesses, universities and nonprofit organizations to establish the National Additive Manufacturing Innovation Institute in Youngstown, Ohio. (Hessman 2012).

It has great potential to reverse the offshoring movement. AM allows manufacturers to produce locally and respond quickly to changes in demand. It increases flexibility and makes proximity to both the design side of business and the demand side because manufacturing can be done effectively and efficiently in smaller units (Magnus 2012).

It will grow. Terry Wohlers estimates the market for 3D prints will grow from approximately $2 billion in 2012 to $6.5 billion by 2019 (Gupta 2012). In a Wall Street Journal article, Michael Malone (2012) lists three-dimensional printing as one of his six sources of the "next American boom." Larger printers will be built to make larger parts. Automobile bodies, airplanes and buildings have been mentioned as future possibilities for AM applications.

Small companies will probably be acquired by larger ones. 3D Systems, one of the two pioneers in the field, has been aggressive in acquiring 20 companies since 2009. Stratasys, the other pioneer, has been more conservative but, as indicated, closed its merger with Objet, an Israel company in 2013. GE and HP appear to be the most likely large companies to grow through acquisition as well as through internal efforts.

One of the most widely referenced websites is http://wohlersassociates.com/additive-manufacturing.html. Mr. Terry Wohlers has been involved in 3D printing since its early days and is an active reporter on advances in the technology.

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Anyone need a new part for your car or house? Just crank up the 3D printer in your garage and make it! However, you may be well advised to outsource making your replacement body parts.

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