A review of recent trends and challenges in 3D printing

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Abstract

The recent developments in 3D printing also known as "Additive Manufacturing" or **AM** have revolutionized the modern manufacturing process and the engineering design process. Emerging use of 3D printing technology is prevalent in automotive, manufacturing, aerospace, pharmaceutical industry & healthcare, fashion, retail and sports. In this paper, the author propose to review the recent trends and challenges in 3D printing technology. The technological advancements in extrusion materials, design & processes, equipment's capability have brought down the cost of manufacturing. The proposed paper will review latest developments in 3D printing material types, manufacturing techniques, equipment types, and the development of standards for selecting material, quality control, and 3D printing machinery.

World demand for 3D printers and related materials and software is projected to rise 21 percent per year to $5.0 billion in 2017 per freedoniagroup[28]. It is about time to educate the future designers, engineers and entrepreneurs on 3D printing. A typical course curriculum is also proposed to add an elective course in the mechanical engineering department in one of the Michigan regional universities.

Introduction

The purpose of this paper is to provide a review of recent trends and challenges in 3D printing. The technological advancements in extrusion materials, design & processes, equipment's capability have brought down the cost of manufacturing. The proposed paper will review 3D printing material types, AM techniques, printer types, and the standards for selecting material, quality control, and 3D printing machinery.

3D printing or additive manufacturing is a process of making three-dimensional solid objects from a digital file. The creation of a 3D printed object is achieved using additive processes. In an additive manufacturing process, an object is created by printing successive layers of material until the entire object is created. Each of these layers is a thinly sliced horizontal cross-section of the object. This process is called additive process, because it uses materials more efficiently than traditional manufacturing techniques, which are subtractive process (such as cutting or drilling).

The recent developments in 3D printing also known as "Additive Manufacturing" have revolutionized the modern manufacturing process and the engineering design process. Emerging use of 3D printing technology is prevalent in automotive, manufacturing, aerospace, pharma & healthcare, fashion, retail and sports.

The 3D printing technology is used for both prototyping and distributed manufacturing with applications in architecture, construction, industrial design, automotive, aerospace, military, engineering, civil engineering, dental and medical industries, biotech (human tissue replacement), fashion, footwear, jewelry, eyewear, education, geographic information systems, food, and many other fields.

The quality of the 3D printed object depends upon the additive material composition, the manufacturing process, the type of 3D printers used, the speed of the printer, and the volume of the object printed. This paper will address each category trends and challenges. Today google search will yield 88.1M hits on 3D printing. The 3D printing technology is becoming a mainstream manufacturing technology similar to metal cutting technology. It is appropriate and timely to offer AM technology courses in the universities.

Literature Review

The idea of printing 3D objects conceptualized and was patented by Chuck Hull [1, 2] of 3D Systems Inc. in 1986. Sachs[3] et al. at MIT obtained a patent for making a component by depositing a first layer of a fluent porous material, such as a powder, in a confined region and then depositing a binder material to selected regions of the layer of powder material to produce a layer of bonded powder material at the selected regions. Such steps are repeated a selected number of times to produce successive layers of selected regions of bonded powder material so as to form the desired component. The un-bonded powder material is then removed. In some cases the component may be further processed, for example, by heating it to further strengthen the bonding thereof. MIT's 3DP™ process laboratory[4] lead the way in 3D printing process research in the area of gradient index lenses, tooling for low cast casting, fine ceramic components for electronic application, tungsten carbide cutting tools, and metal matrix composites.

D.A. Roberson[5] et al. evaluated the capability of five desktop additive manufacturing (AM) machines based on the ability to produce a standard component. This work also developed a model/method for evaluating and ranking AM technologies based on select criteria that can facilitate purchasing decisions. A standard part was designed and printed on each machine, and evaluated based on dimensional accuracy and surface finish. Additionally, the machines were compared based on build time for single and multiple parts as well as material consumption and unit cost. The ranking system presented in this paper has demonstrated the ability to discriminate between different AM processes and rank these systems based on quantitative measures.

Lee and Kim[6] analyzed the trend of 3D printing-related patents for the last 10 years to investigate patent application trends by country, by year, by assignee and by technology. Furthermore, the paper analyzed the patent trend on 3D printers and materials used to secure original technologies and a portfolio of application technologies in medium and long terms. Utela[7] et al. presented a paper organizing the process of 3DP implementation into five steps (powder formulation, binder method selection, binder formulation and testing, printing process specification, and post-processing specification) and presented a review of the literature relevant to each step in 3DP implementation. Huang[8] et al. reviewed the societal impact of additive manufacturing in (1) customized healthcare products to improve population health and quality of life, (2) reduced environmental impact for manufacturing sustainability, and (3) simplified supply chain to increase efficiency and responsiveness in demand fulfillment. Their review also identified the need for further research in the areas of life-cycle energy consumption evaluation and potential occupation hazard assessment for additive manufacturing.

Berman[9] in his paper examined the characteristics and applications of 3D printing for mass customization. He argued that there are a number of promising applications exist in the production of replacement parts, dental crowns, and artificial limbs, as well as in bridge manufacturing. 3D printing market allow firms to profitably serve small market segments, and enable companies to operate with little or no inventory and significantly reduce the need for factory workers. Thompson[10] et al. provided an overview of the major advancements, challenges and physical attributes related to Direct Laser Deposition (DLD) process. The Part I focused on the thermal/fluidic phenomena during the powder-fed DLD process, which directly influence the solidification heat transfer, which thus affects the part's microstructure and associated thermo-mechanical properties. In Part II Shamsaei[11] et al. focused on the mechanical properties, characteristics, behavior and microstructure of parts manufactured via DLD and post DLD process parameters (e.g. heat treatment, machining). Methods for controlling/optimizing the DLD process for targeted part design discussed – with an emphasis on monitored part temperature and/or melt pool morphology.

Singh[12] et al. reviewed the recent technological advancements in materials and in technological aspects of 3D printing, identified future challenges and potential applications in engineering, manufacturing and tissue engineering. Also provided number of patents filed in materials, their applications and industry-wise patent filing trends.

The overall 3D printing technology publishing trend[16] is provided in Figure 1. The exponential rise in the number of publications clearly demonstrates that 3D printing technology is going to dominate the additive manufacturing filed in the coming years.

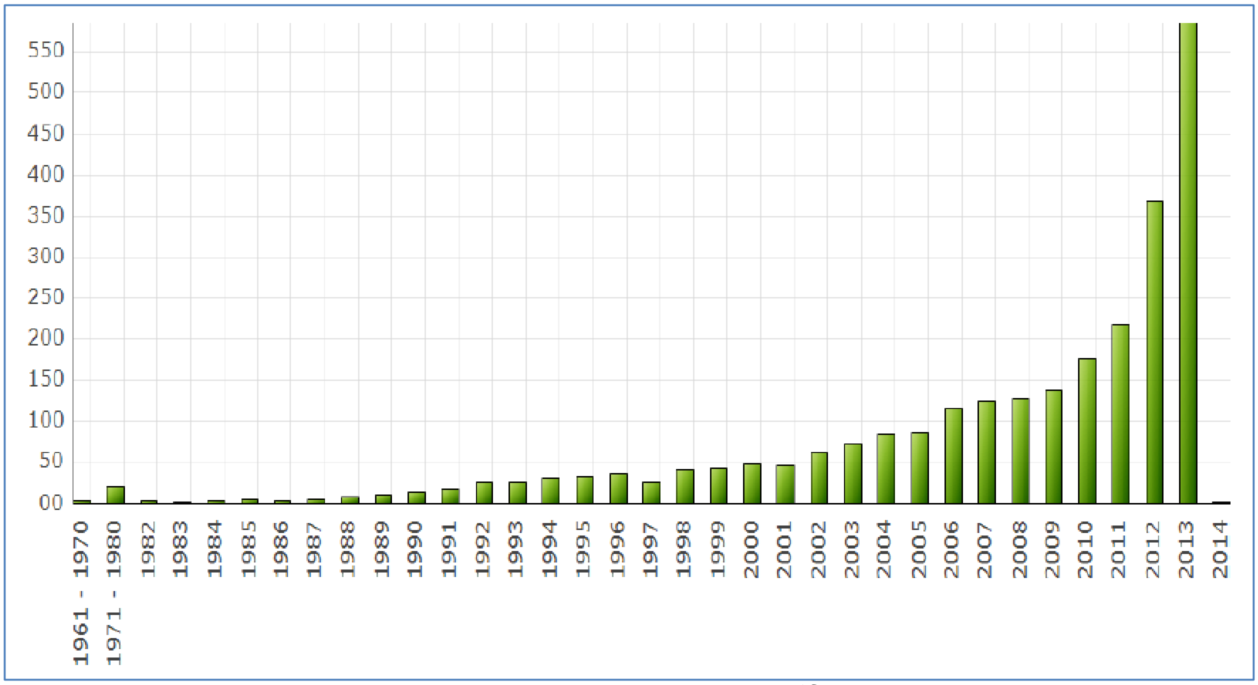

Figure 1: Publication Trend[16]

The overall 3D printing patent publication trend[16] is provided in Figure 2. The exponential rise in the patent applications clearly demonstrates that 3D printing technology is going to dominate additive manufacturing in the coming years.

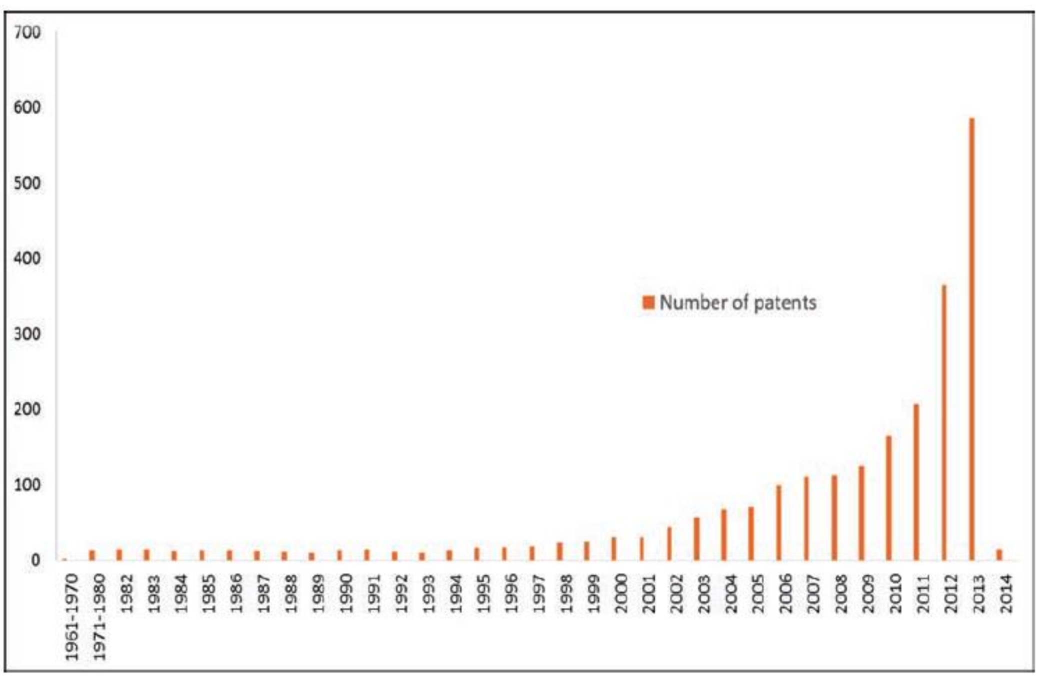

Figure 2: Patent applications trend[16]

The following sections will focus on the material, printing technology, 3D printing equipment and part quality issues and standards.

3D Printing Materials[13, 14]

Materials in additive manufacturing technology systems are defined by the fabrication processing technology. Each 3D printing technology transforms material through external heat, light, lasers and other directed energies. The ability of a material's mechanical composition to react positively to a certain directed energy marries that material to a technology which can deliver the desired change. These material-technology partnerships will expand as materials are advanced and material chemistry explored. Advancing technologies encourages more positive material reactions, layer by layer, to directed external energies. The mechanism of material change-unique to individual 3D printing technologies and processes-defines the material in terms of state changes, final mechanical properties and design capabilities. By extension, developments in 3D printing materials correspond with developments in 3D manufacturing; as the build process improves to encourage more positive reactions from materials, material selections will expand.

The 3D printing materials are available in different material types and states such as powder, filament, pellets, granules, resin etc. Specific material types and material properties are developed more precisely to suit the application. There are plenty of materials already available. New materials are being developed as the new applications are emerging for 3D Printing. In this section the most popular types of AM material types are reviewed.

Plastics
Nylon, or Polyamide, is a strong, flexible, reliable and durable plastic material commonly used in powder form with the sintering process or in filament form with the Fusion Deposition Modeling (FDM) process. It is naturally white in color but it can be colored pre -or post-printing. This material can also be combined (in powder format) with powdered aluminum to produce another common 3D printing material for sintering- Alumide. ABS is another strong plastic used for 3D printing, in filament form. It is available in a wide range of colors.

Polylactic acid or polylactide (PLA) is a biodegradable plastic material be utilized in resin format for digital light processing/stereolithography (DLP/SL) processes as well as in filament form for the FDM process. It is offered in a variety of colors, including transparent, which has proven to be a useful option for some applications. However, it is not as durable or as flexible as ABS.

LayWood is a specially developed 3D printing material for entry-level extrusion 3D printers. It comes in filament form and is a wood/polymer composite (WPC). This special filament is a composite material of recycled wood and polymer parts that can create wood-like objects that have the look, feel and even the smell of wood. It can be printed between 175-250^{0}C. It is available in light and dark color wood.

Metals
The most common metals and metal composites are titanium, aluminum and cobalt derivatives. One of the strongest metals for 3D printing is stainless steel in powder form for the

sintering/melting/electron beam melting processes. It is naturally silver, but can be plated with other materials to give gold or bronze effect applications across the jewelry sector.

Ceramics
Ceramics are a relatively new group of materials that can be used for 3D printing with various levels of success. The ceramic parts need to undergo post-processing processes same as any ceramic part made using traditional methods of production — namely firing and glazing.

Paper
Mcor[14]Technologies' paper-based 3D printers use the proprietary **S**imple **D**irectMedia **L**ayer (SDL) process. SDL process based 3D printers provide arts community with unlimited access to professional class 3D printing technology. 3D printed models made with paper are safe, environmentally friendly, and easily recyclable and require no post-processing.

Bio Materials[15]
Material from biological origin instead of fossil fuels. There is a huge amount of research being conducted into the potential of 3D printing bio materials for a host of medical (and other) applications. Living tissue is being investigated at a number of leading institutions with a view to developing applications that include printing human organs for transplant, as well as external tissues for replacement body parts.

Food
Experiments with extruders for 3D printing food substances have increased dramatically over the last couple of years. Chocolate is the most common (and desirable). There are also printers that work with sugar and some experiments with pasta and meat. Looking to the future, research is being undertaken, to utilize 3D printing technology to produce finely balanced whole meals.

Other[14]
Stratasys' Objet Connex 3D printing platform printing process combines various materials and specified concentrations to form new materials with the required properties. Up to 140 different Digital Materials can be realized from combining the existing primary materials in different ways.

A comprehensive list of materials applications used by the various manufacturers is shown in Figure 3.

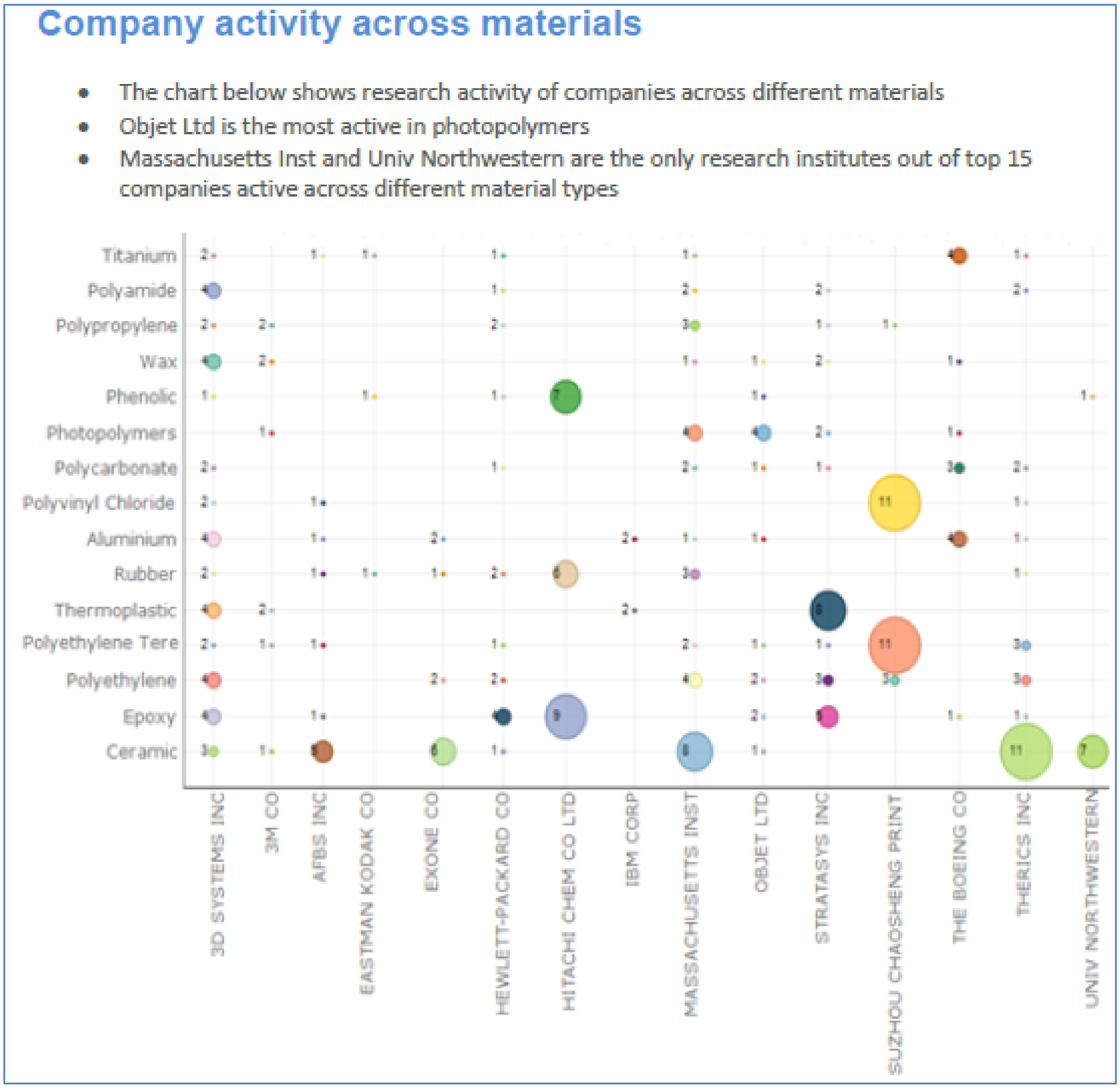

Figure 3: Materials vs 3D Printing manufactures[16]

Printing Technology overview

There are many different 3D printing technologies and different classifications of these technologies are used. The American Society for Testing and Materials[18] (**ASTM**) have divided the additive manufacturing technologies in 7 process categories, which are shown in the Table 1 between brackets. The 3D technologies and materials are shown in Figure 4.

PROCESS (ASTM PROCESS)	TECHNOLOGY (SOME EXAMPLES)
EXTRUSION	Fused Deposition Modelling (FDM)
(MATERIAL EXTRUSION)	A material is melted and extruded in layers, one upon the other *(This technique is normally used in 3D printers at home)*
DIRECT ENERGY DEPOSITION	Electron Beam Direct Manufacturing (EBDM)
(DIRECT ENERGY DEPOSITION)	An electron beam melts a metal wire to form an object layer by layer
SOLIDIFICATION OF POWDER	Selective Laser Sintering (SLS)
(POWDER BED FUSION)	A bed of powder material is "sintered" (hardened) by a laser, layer upon layer until a model is pulled out of it
SOLIDIFICATION OF POWDER	3D Printing
(BINDER JETTING)	Powder is bond by a binding material distributed by a movable inkjet unit layer by layer
PHOTO-POLYMERIZATION	Stereolithography (SLA)
(VAT PHOTO-POLYMERIZATION)	Concentrating a beam of ultraviolet light focused onto the surface of a vat filled with liquid photo curable resin. The UV laser beam hardening slice by slice as the light hits the resin. When a projector beams the UV-light through a mask onto the resin it is called Digital light processing (DLP)
PHOTO-POLYMERIZATION	Polyjet Process
(MATERIAL JETTING)	A photopolymer liquid is precisely jetted out and then hardened with a UV light. The layers are stacked successively
SHEET LAMINATION	Laminated Object Manufacturing (LOM)
(SHEET LAMINATION)	Layers of adhesive-coated paper, plastic, or metal laminates are glued together and cut to shape with a knife or laser cutter

Table 1: Technology overview based on process[15]

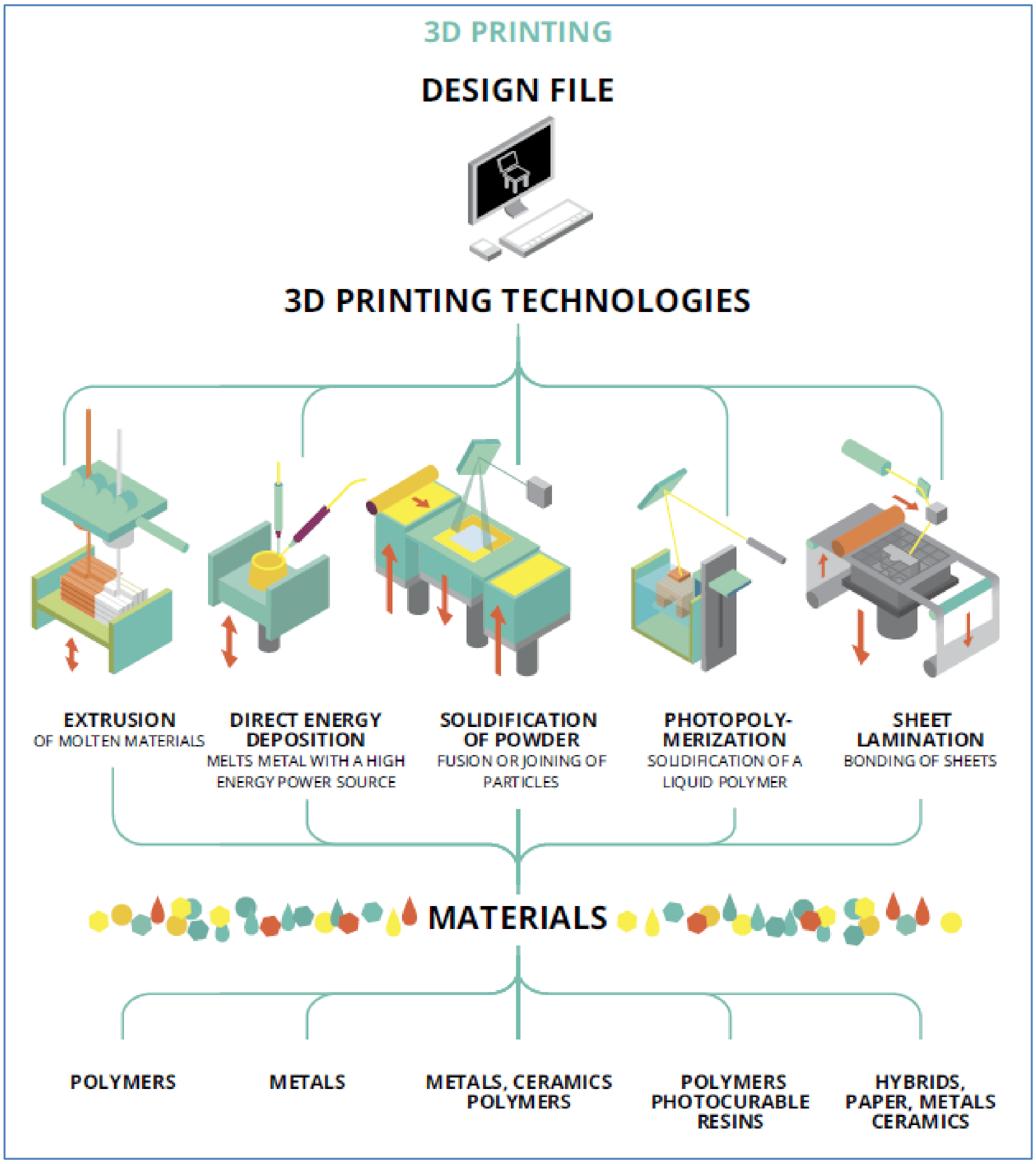

Figure 4: Materials and technology[15]

3D printing or additive manufacturing refers to several technologies that produce parts in an additive way. Figure 5 provide an overview of the technologies by the type of material they work with (vertical axis) and how the parts are built out of this material (horizontal axis). Starting point is a digital 3D model of a part, which is then "sliced" in thin layers by a specific computer software. An additive manufacturing machine is building these layer on top of another and thus is creating the physical part.

In order to understand the potential of additive manufacturing, it is crucial to understand the technologies behind it. How the parts are built has an impact on the characteristics such as, durability, surface finish, details and application.

Polymerization means that parts are built through a UV-light activated polymerization of a chemically reactive liquid material. **Bonding agent** means that powder material is glued together through a liquid bonding agent. **Melting** means that material is melted together.

Depending upon the require part characteristics, additive manufacturing technologies are either used directly to produce parts or by indirect processes in combination with traditional manufacturing techniques.

Direct processes: The part is directly produced with the additive manufacturing machine. There are post-processes applied in order to improve tolerances or surface finish.

Multi-stage process: A "green" part is produced with the additive manufacturing technology which is then going into further processes. For instance, binder jetting is used to produce green metal parts (where metal powder is glued together) which are then going into a sinter process and are infiltrated afterwards.

Indirect processes: Additive manufacturing can be combined with traditional manufacturing. For instance, master patterns are made with 3D printing technologies, which are then used for investment casting of final parts.

The 3D printing technology is an evolving technology. It can be summarized based on 3D printing materials used or based on the processes used or by the 3D printer construction.

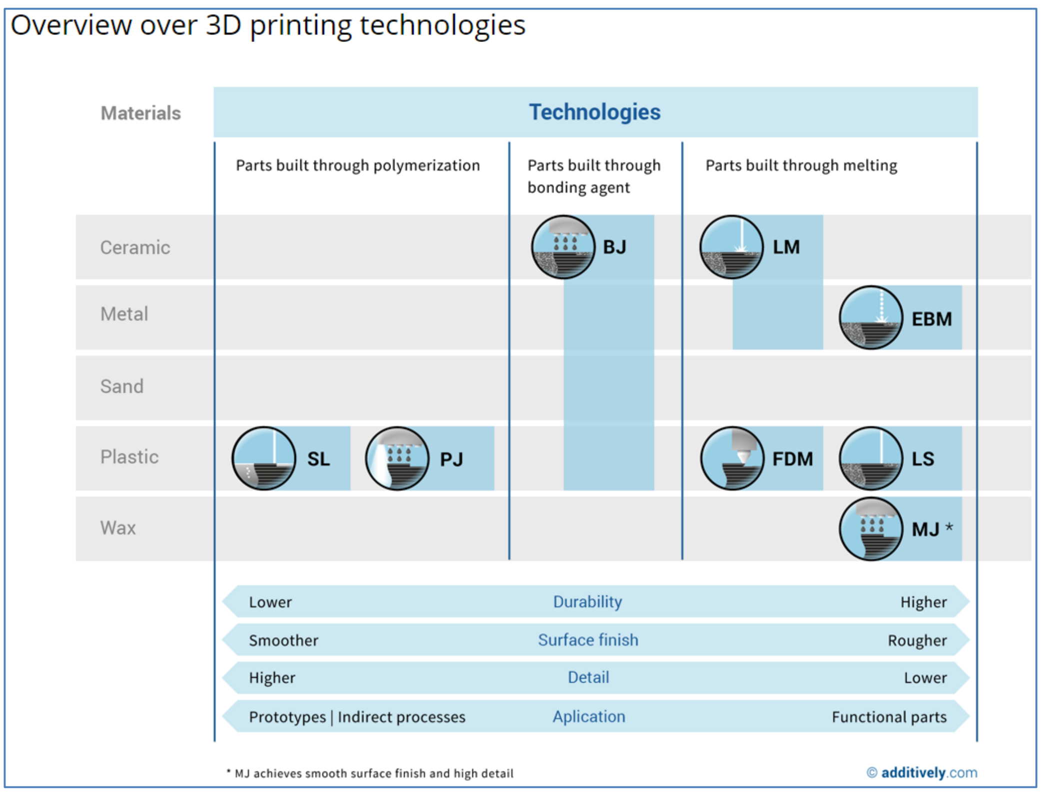

Figure 5: Technology overview based on material[17]

Stereolithography (SL)
In this process, a UV laser is curing a liquid photopolymer in a vat. The part is built by lowering the build platform into the vat. Stereolithography can build large parts with very good accuracy and surface finish. A wide range of material allow to build parts with specific characteristics. However, stereolithography only works with photopolymers which are not stable over time and have no well defined mechanical properties. Prototypes are built with fine details, very good accuracy and surface finishes for visual, form / fit and sometimes functional testing. Materials have been specifically developed to mirror the mechanic properties of engineering materials (in the short term), e.g. high heat resistance. Casting patterns are produced with stereolithography as very good accuracy and surface finishes are achieved.

Photopolymer Jetting (PJ)
In this process, an inkjet print heads are used to jet liquid photopolymers onto a build platform. The material is immediately cured by UV lamps and solidified which allows to build layers on top of each other. Please refer Figure 13. Multiple materials can be jetted together allowing multi-material and multi-color parts. Functionally graded materials are possible.

Binder Jetting (BJ)
In this process, an inkjet print heads apply a liquid bonding agent onto thin layers of powder. By gluing the particles together, the part is built up layer by layer. Binder jetting technology works with a wide arrange of material types. Green parts are produced to be further processed with other manufacturing techniques. For instance metal parts are sintered in an oven process and then infiltrated.

Laser Melting (LM)
In this process, a thin layer of metal powder is selectively melted by a laser. The parts are built up layer by layer in the powder bed. Please refer Figure 10. Laser melting can manufacture parts in standard metals with high density, which can be further processed as any welding part. However, the technology is rather slow and expensive as well as surface finishes are limited.

Fused Deposition Modeling (FDM)
In this process, a plastic filament is melted and extruded through a nozzle. Parts are built by laying down layer-by-layer. Fused deposition modeling can build fully functional parts in standard plastics. However, they have an anisotropy in the z-direction (vertical direction) and a step-structure on the surface.

Electron Beam Melting (EBM)
In this process, a thin layer of metal powder is selectively melted by an electron beam. The parts are built up layer by layer the in the powder bed. Please refer Figure 8. The parts can be manufactured in using standard metals with high density by electron beam melting. However, the availability of materials to melt is limited and the process is rather slow and expensive. One of a kind small parts are produced directly by electron beam melting (post-processing to achieve better tolerances and surface finish might be required).

Laser Sintering (LS)
In this process, a thin layer of plastic powder is selectively melted by a laser. The parts are built up layer by layer in the powder bed. Please refer Figure 11. Laser sintering can manufacture parts in standard plastics with good mechanical properties. There is a constantly growing set of materials available. However, parts do not have exactly the same properties as their injection molded counterparts.

Material Jetting (MJ)
In this process, an inkjet print heads are used to jet melted wax materials onto a build platform. The material cools and solidifies which allows to build layers on top of each other. Please refer Figure 12. Material jetting can achieve very good accuracy and surface finishes. However the technology only works with wax-like materials.

Printing Equipment [19]

The 3D Systems Inc. is one of the top 3D printer manufacturing company in the world. The 3D printers are available in broad range from small desktop, professional to full production types. The mantra for the 3D printing companies' is "if you can imagine it, we can print it".

The top 10 3D printing manufactures are 1) 3D Systems Inc., 2) Stratasys Inc., 3) MIT, 4) Hewlett-Packard Co., 5) Hitachi Chemical Co., 6) Matsushita Electric, 7) Therics Inc., 8) Materialise NV, 9) Objet Ltd., 10) Panasonic Corp.

Bio printers

3D bio printers are based on proprietary version of a basic syringe/pressure-based extrusion of both paste-like polymeric substances and hydrogels (also known as bio inks in certain cases), which are basically gel-like substances containing high quantities of water and living cells. There are several variations and alternatives available. There are many varieties of printers' available in the price range from $10K to > $200K depending upon the complexity of the printing technology.

The 3D-Bioplotter® System[29] is a versatile Rapid Prototyping tool for processing a great variety of biomaterials for Computer Aided Tissue Engineering (CATE), from 3D CAD models and patient CT data to the physical 3D scaffold with a designed and defined outer form and an open inner structure.

Technology: syringe-based extrusion
Materials: hydrogels, silicone, hydroxipa

Machine Specifications:
Axis Resolution: (XYZ) – 0.001mm (.00004″)
Speed: 0.1 – 150 mm/s (0.004” – 5.91”/s)
Build Volume (XYZ): 150 x 150 x 140 mm (5.91” x 5.91” x 5.51”)
Minimum Strand Diameter: 0.100 mm (0.004”) – Material Dependent

OneUp
The OneUp[30] is the cheapest 3D printer in the world under $200. With Oneup, the professional quality prints are a reality, equivalent to much more expensive machines at competitive speeds with the ability to expand the build area at any time. Each kit includes a very reliable and forgiving extruder that makes it easy to get great quality prints with minimal effort. This is a Do-It-Yourself, Self-Assembly kit that generally takes 2-8 hours to assemble based on end user skill level.

Machine Specifications:
Technology: Fused Filament Fabrication
Build Area: 100mm x 100mm x 125mm
Layer Resolution: 50 Microns
Filament Diameter: 1.75mm
Nozzle Diameter: .40mm
Minimum Feature Size: .20mm
Maximum Extruder Temperature: 250c

Witbox
There are varieties of 3D printers available in various size, shape, & and form to fit anyone's budget under $2500. One such printer is Witbox[31] from a Spanish manufacturer.

Machine Specifications:
Print Area: 210 x 297 x 200 mm
Layer Thickness: 0.05 mm
Features: LCD screen with SD card reader, three-point leveling system, vibration damping,
Materials: PLA, ABS

Winsun
The biggest 3D printer by far is the one created by a Chinese company. Winsun[32] printer is capable of building furniture, houses, and even five story buildings. The best part of Winsun technology is that it uses recycled concrete from construction waste, and the process is therefore significantly friendlier to the environment than traditional construction. Winsun is building 100 recycling facilities around China to keep up with demand.

Machine Specifications:
Print Area: 132' (40m) x 33' (10m) x 22' (6.7m)
Materials: recycled concrete

Creating Better Prints[19]

The following criteria affect the quality of the 3D printed parts:

1. Design process: Wall thickness, overhang (<45 degree); support; support gap; create span instead of overhang; part shrinkage; provide chamfer instead of fillet.

2. Software: Select appropriate slicer conversion program- slicing program generates the G-code necessary to feed into the 3D printer.
3. Equipment: Basic machine maintenance; filament quality; temperature; speed.

Part quality issues[20]

The 3D printing is a developing technology, so the part quality issues are discovered everyday based on the material types, complexity of the part design and the capability of the printers. The major defect categories are based on:

- Material feed_ such as defect caused by excessive or insufficient material or handling or clogged or temperature or printer speed or calibration or bed adhesion
- Printer_ the part defect might occur due to not starting at the start of the print or at the end of the print
- Print defects_ Surface deflects such as Pitting/Holes, Jagged edges, Stringy prints, Infill gaps to perimeter, body defects such as holes undersized, bridging failure such as warping, steeping/offsetting, interlayer delamination, layer shifting
- Computer freeze up or communication failure
- Overheating of the machine itself may cause damage to the part

Standards[21]

As AM technology is becoming mainstream technology, it is necessary to develop a set of quality standards to define the AM materials, printers, and the part quality without harming the growth of the technology. ISO and ASTM committee are developing the following general AM standards.

ISO/ASTM 52900:2015	General principles
ISO 17296-2	Overview of process categories & feedstock
ISO/ASTM 52921:2013	Co-ordinate systems & test methodologies
ISO 17296-3: 2014	Main characteristics and test methods.

The UL laboratories[27] developed set of safety standards for the 3D printers. These standards address the hazards based on:

- Operating environments_ who intend to interface with the printer
- Application_ where it is used (school, home, industrial, food preparation, medical)
- Machinery_ potential hazards with the design of the 3D printers
- School_ For use by children in school
- Emissions_ regulations associated with airborne emissions
- Explosive_ regulations associated with explosive atmosphere

Typical Academic Curriculum

The additive manufacturing course is being developed and will be offered in future when the resources become available.

Course title: ME 450 Additive Manufacturing: Part design, theory and practice (3 credit)

Course Description and Goals:
Additive manufacturing (AM) technologies fabricate 3D parts using layer-based manufacturing processes directly from CAD models. In this course, students will learn about AM part design, AM theory, material types, printing technologies, and quality issues by extruding parts using STRATASYS, INC. Model: BST 1200es / SST 1200es 3D printer.

Upon successful completion of the course, students should be able to:

- Provide comprehensive overview of the AM technologies
- Create a CAD design suitable for AM process
- Use commercial software for digitizing free-form geometry
- Compare traditional manufacturing versus AM manufacturing
- Understand the various quality defects in AM manufacturing
- Operate the lab 3D printer independently thru lab exercises

Text Book:
Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, 2nd Ed. (2015), Ian Gibson, David W. Rosen, Brent Stucker
ISBN-13: 978-1493921126; ISBN-10: 1493921126

Conclusion

Additive Manufacturing (AM) often referred as 3D printing is experiencing an unprecedented growth. Some predict AM might even replace the traditional manufacturing someday. The AM technology is used in Tissue Engineering followed by automobile, mechanical, jewelry, tooling, clothing, television, phones, PCB, aerospace, toys, watches, scaffolding, robotics, prosthesis, food industry and construction. The multi-material jetting head[22] that could print multiple materials including metals, plastics, ceramics, enzymes, and biological cells. The 3D printing is evolving in to 4D- printing[23] at MIT's self-assembly lab. The big idea is to create objects that can change after they are printed, making them self-adapting. The act of printing is no longer the end of the creative process but merely a waypoint. 4D printing process where shape memory polymer fibers could fold, stretch, curl or twist when allowed the environmental exposure changes [24]. When a heart is damaged during a major heart attack, scientists have now engineered tissue that closely mimics natural heart muscle that beats, not only in a lab dish but also when implanted into animals[25]. AM technology is classified as a one of the twelve disruptive technologies[26] that will transform life, business, and the global economy. The 3D printing technology even got the attention of the US president in his recent union address.

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Biography

Dr. Annamalai Pandian is an assistant professor at Saginaw Valley Sate University. He earned his B.Eng. & M.Eng. Degree in Mech. Eng. from the University of Madras, Chennai, India, and M.S Degree in Mech. Eng. from Louisiana State University, Baton Rouge, LA, USA and D. Eng., Degree in Manufacturing Systems from Lawrence Technological University, Southfield, MI, USA. He has wide range of industrial experience in sheet metal stamping, robotic welding, automation, product design, project management, six sigma and lean manufacturing methods. He has very good certification knowledge on ISO 9001 standards and procedures. He taught in the University of Wisconsin-Stout for few years before moving to Saginaw Valley State University. He has worked in the Advanced Manufacturing Engineering division in Chrysler LLC, Auburn Hills, MI, USA for 13+ years. He has wealth of experience in automotive tooling design, process and manufacturing. He has taught several mechanical, design and manufacturing engineering courses including Engineering Mechanics, CAD, Jigs & Fixtures, Robotics & Machine Vision, Manufacturing Process Eng., Manufacturing Systems Design and Simulation, and Lean Manufacturing. Dr. Pandian's research interests include 3D printing, Sheet metal forming, Simulation, DOE, Robotics, ARMA and ANN. He is a member of ASQ, ASEE, IEOM, IIE, and SAE.

Mr. Cameron Belavek is an undergraduate Engineering Technology Management student at Saginaw Valley Sate University. He is doing research work in the area of 3D printing using Solidworks CAD models. He is also working as a co-op student at Dow Corning Corporation, Midland, MI. He created 3D models using CAE software for FEA and CFD simulation/analysis. He developed mechanical technologies to 3D print advanced materials. He is responsible for designing and 3D printing variety of parts for many different applications. He modeled hyperelastic materials using ANSYS software. He designed various tools/structures to be used in manufacturing/assembly operations. He is well-versed in SolidWorks, SimulationXpress Analysis, ANSYS, Static Structural Analysis, Thermal Analysis, 3D Printing on Stratasys uPrint Plus (ABS), MakerBot Replicator 2X (ABS & PLA).

References

[1] http://www.google.com/patents/US4575330#v=onepage&q&f=false
[2] http://www.3dsystems.com/30-years-innovation
[3] Sachs, E.M., Haggerty, J.S., Cima, M.J., Williams, P.A., "Three-dimensional printing techniques, US patent 5,204,055" 1989 http://www.google.com/patents/US5204055 retrieved on 1/8/2016.
[4] http://web.mit.edu/tdp/www/research.html
[5] Roberson, D.A., Espalin, D., & Wicker, R.B., "3D printer selection: A decision-making evaluation and ranking model", Virtual and Physical Prototyping, 2013, 8:3, 201-212
[6] Lee, I. and Kim, Y., "The Recent Patent Analysis and Industrial Trend of 3D Printing", Indian Journal of Science and Technology, Vol 8(S8), 70-73, April 2015
[7] Utela, B., Storti, D., Anderson, R., & Ganter, M., "A review of process development steps for new material systems in three dimensional printing (3DP), Journal of Manufacturing Processes 10 (2008) 96-104
[8] Huang, S.H., Liu, P., Mokasdar, A., & Hou, L., "Additive manufacturing and its societal impact: a literature review" International Journal of Advance Manufacturing Technology (2013) 67:1191–1203
[9] Berman, B., "3-D printing: The new industrial revolution", Business Horizons (2012) 55, 155—162
[10] Thompson S.M., Bianc, L., Shamsaei, N., & Yadollahia, A., " An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics", Additive Manufacturing 8 (2015) 36–62, http://dx.doi.org/10.1016/j.addma.2015.07.001
[11] Shamsaei, N., Yadollahia, A., Bianc, L., & Thompson S.M.," An overview of Direct Laser Deposition for additive manufacturing;Part II: Mechanical behavior, process parameter optimization andcontrol", Additive Manufacturing 8 (2015) 12–35, http://dx.doi.org/10.1016/j.addma.2015.07.002
[12] Singh,O.P., Ahmed, S.M., & Abhilash, M., "Modern 3D Printing Technologies: Future Trends and Developments", Recent Patents on Engineering, 2015, 9, 91-103
[13] http://3dprintingindustry.com/3d-printing-basics-free-beginners-guide/materials/
[14] https://www.stratasysdirect.com/resources/choosing-the-right-material-for-your-application/
[15] Wijk, AV. & Wijk, I.V., “3D Printing with Biomaterials”, published by IOS PRESS BV, Amsterdam, The Netherlands.2015.
[16] https://gridlogics.com/

[17] https://www.additively.com/en/learn-about/3d-printing-technologies#read-chain
[18] American Society for Testing and Materials. www.astm.org
[19] http://support.3dverkstan.se/article/30-getting-better-prints
[20] https://www.simplify3d.com/support/print-quality-troubleshooting/
[21] http://www.iso.org/iso/iso_technical_committee?commid=629086
[22] http://www.ttp.com/corporate/press/
[23] http://www.wired.com/2013/02/4d-printing-at-ted/
[24] Ge, Q., H. Jerry Qi, J.H., Martin L., & Dunn, M.L., "Active materials by four-dimension printing" Appl. Phys. Lett. 103, 131901 (2013); http://dx.doi.org/10.1063/1.4819837
[25] http://www.tissueeng.net/lab/research-tissueeng.php Biomed. Mater. 10 (2015) 034006
[26] http://www.mckinsey.com/insights/mgi
[27] http://ulstandards.ul.com/
[28] www.freedoniagroup.com/
[29] http://envisiontec.com/3d-printers/3d-bioplotter/
[30] http://q3dprinter.com/oneup.htm
[31] http://www.bq.com/es/witbox-2
[32] http://www.yhbm.com/index.php?m=content&c=index&a=lists&catid=72