

3D printing – challenges and perspectives

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This paper presents the systematic classification of the existing 3D printing processes, their operating principle, scope of application, materials that can be used, as well as some economic aspects. This is a review article, based on information available from public sources. The paper proposes a few examples of the practical application of some of these 3D printing processes. Keywords: 3D printing, additive manufacturing, desktop manufacturing, manufacturing-on-demand.

Introduction

The main technologies used for manufacturing machine parts and other 3D items until the 1980s were:

- Subtractive manufacturing (cutting, drilling, grinding, polishing...);
- Moulding;
- Forging;
- Die cutting etc.

During the 1980s a new way of manufacturing emerged. Instead of successive cutting from a solid block of material (subtractive manufacturing)¹, the material is added layer by layer onto an appropriate platform. The new layer adheres to the previous one and, if it is in a form of powder or a liquid, solidifies. This new way of manufacturing is called "additive manufacturing"², but there are other names in use: DeskTop Manufacturing, Rapid Manufacturing, Manufacturing-on-Demand or 3D Printing. The additive manufacturing process is partially digital, it is controlled by a computer system, and the object is mathematically defined. However, some parts of the processes could be analogue because they depend on temperature or the intensity of radiation. Additively manufactured objects could have a complex shape, which cannot be easily (or at all) achieved by

subtractive manufacturing. Information about the shape, dimensions as well as its composition are recorded as AMF Additive Manufacturing File or STL file³.

Some futurologists, for instance Jeremy Rifkin, classify 3D printing into discoveries that will allow the start of the third industrial revolution⁴, which is supposed to be the successor of the old mode of production, the dominant approach to the production of the late 19th century, based on the production line and intended for the production of a large number of identical pieces.

This paper will review the existing 3D printing technologies, working principles, materials and a possible field of application of those processes.

Historical overview and standardization

The beginning of the development of 3D printing processes is connected to the article "A Scheme for three-dimensional display by automatic fabrication of three-dimensional model" that was published in 1981 by Hideo Kodama. He created two methods used for the formation of a three-dimensional object from liquid photosensitive polymer composition by controlled UV radiation.

In 1984, a group of French inventors, Alain Le Méhauté, Olivier de Witte and Jean Claude André, filed a patent for the stereolithography processes, that their company rejected on the grounds that innovation lacks business prospects.⁵

Only three weeks after the French group, Chuck Hull also filed his patent application for stereolithography (SLA).

The development of the now widely accepted STL file format (STereoLithography) is also one of Hull's great contributions.⁶

In 1986, the Company Helisys patented a method of forming a 3D object by laminating layers, called Laminated Object Manufacturing – LOM. This procedure has entered into commercial use in 1991.⁷ In 1986, the DTM company patented a process Selective Laser Sintering – SLS, which was conceived by Carl Deckard, who was an undergraduate student at the time.⁸

Three years later, in 1989, MIT patented a process based on the application of the binder sprayed onto the powder surface (3D Printing Process – 3DP).⁹

In that year, Scott Crump patented the technology of 3D printing called Fused deposition modelling – FDM. It was based on modelling by applying molten material. With his wife Lisa, Crump also founded a company called Stratasys.¹⁰

Since 2005, when some patent rights for FDM expired, an open-source community has launched a RepRap project¹¹, which is a real democratization of 3D printing. One of the goals of this project is, for example, a 3D printer that can make the most of its parts. Modern methods of additive manufacturing, categorized into seven categories, according to ISO/ASTM52900-15 (Standard Terminology for Additive Manufacturing – General Principles – Terminology, 2015), and defined by ISO (TC 261), subcommittee F42.91 are:¹²

1. Binder Jetting
2. Directed Energy Deposition
3. Material Extrusion
4. Material Jetting
5. Powder bed fusion
6. Sheet Lamination
7. Vat Photopolymerization

3D workflow

There are a lot of similarities between manufacturing based on digital 2D and 3D printing processes. Manufacturing based on 2D processes could be divided into three main stages: prepress, press and post press. Similarly, 3D workflow could be divided into three stages: modelling, printing and Post processing. Each of those stages could be further divided.

Table 1 Main stages of 2D and 3D printing processes

2D printing stages:		
Prepress	Press	Post Press
Design Software; Scanner; Digital camera; Imposition software.	RIP; Digital printing.	Folding; Collating; Cutting; Sewing; Gluing.
3D printing stages:		
Modeling	3D Printing	Post processing
CAD software; Photogrammetry; Digital camera; 3D scanner; Manual modeling.	Slicing (similarly as RIP creating file for printing on digital press); Creating of additional structures. Main manufacturing process.	Thermal; Chemical; By light; Mechanical.

Binder Jetting – 3DP

Another name for this type of process describes it more precisely: powder bed and ink jet head 3D binder printing process. This process is based on depositing the appropriate bonding fluid onto a thin layer of powder (fig. 1). The powder impregnated with the bonding fluid becomes solid and connected with an underlying solid layer. After the bonding fluid is printed, another layer of powder is applied and the process continues. Non bonded powder remains as a support, surrounding solid parts. When the manufacturing is finished, the remaining powder is removed, and can be re-used.

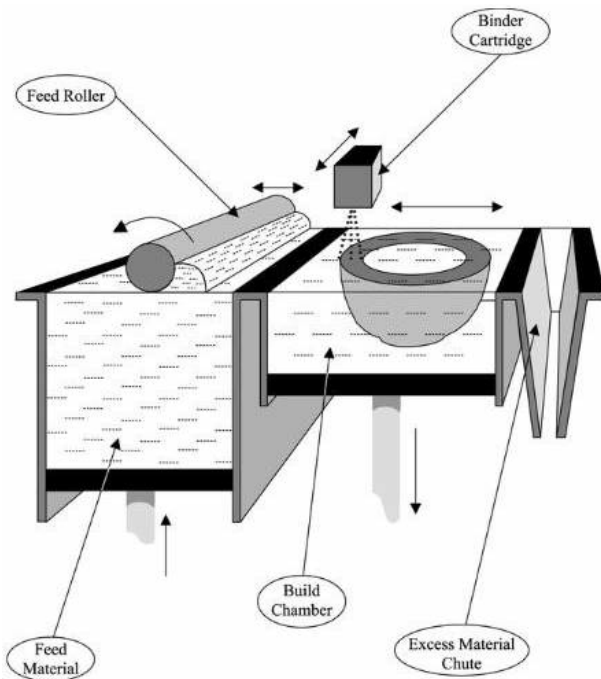


Figure 1. Schematic representation of the 3DP¹³

3DP enables manufacturing coloured objects by combining powders and binders of different colours. By choosing the appropriate powder (alloys, polymers, ceramics, composites), it is possible to achieve the desired mechanical and other properties of the manufactured object.

The process is relatively quick, and could create relatively large objects (fig. 2). It is possible to manufacture large objects of a complex geometry, because there is a supporting material surrounding it. If a powder of a different colour is combined, it is possible to obtain coloured objects. However, post processing is often necessary for enhancing mechanical properties.



Figure 2. Example of large object printed in 3DP¹⁴

Directed energy deposition (DED)

This process is also called: Laser Engineered Net Shaping (LENS), Direct Light Fabrication, Direct Metal Deposition, and 3D Laser Cladding. A high energy laser or an electron beam melts the metal powder or wire, delivered precisely in the focus of the beam (Fig. 3).

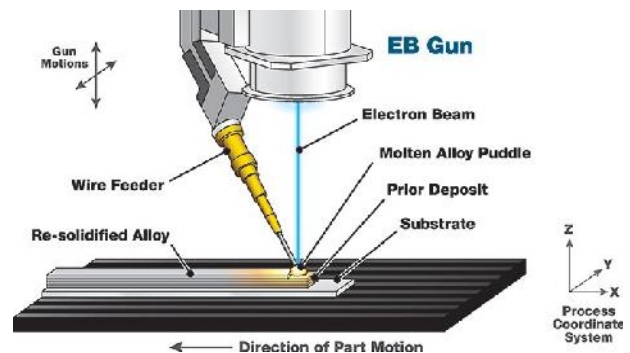


Figure 3. Schematic representation of DED¹⁵

The object is positioned on the supporting platform which moves in a horizontal direction (x-y). The deposition head moves vertically (z-direction) after every printed layer. There are systems with a chamber filled with inert gas, for processing oxygen sensitive materials. DED processes can manufacture new objects as well as repair damaged objects, by adding new material. Objects could be manufactured out of a broad range of metals, including titanium, steel, aluminium, tantalum, niobium, molybdenum, tungsten, Inconel and other alloys. It is possible to combine different materials for manufacturing one object.

Material extrusion

This type of process could be further divided into:

- Fused deposition modeling (FDM), and
- Robocasting, or direct ink writing (DIW).

FDM is trade mark of Stratasys company, and open source community coined a new term for the same type of process: Fused filament fabrication (FFF). FDM (or FFF) is appropriate to process thermoplastics (Acrylonitrile Butadiene Styrene – ABS, Polylactic acid – PLA, Polycarbonate – PC, Polyamide – PA, Polystyrene – PS, high impact polystyrene – HIPS, high density polyethylene – HDPE, polyphenylsulfone

– PPSU) and metals with low melting point. The fig.4 depicts how FDM works. A filament passing through the hot tube is melting and it is precisely deposited through the nozzle onto previously deposited material. Melted material quickly solidifies and bonds to previously deposited material.

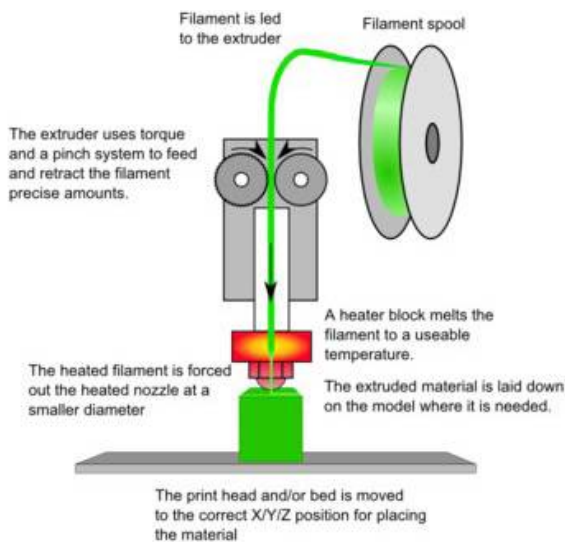


Figure 4. Schematic representation of FDM¹⁶

FDM is one of the 3D printing processes which is the most affordable for a wide range of user. Since the patent rights expired, the price of 3D printers (fig. 5) has constantly decreased (under 500 \$ for a desktop model, in the year 2016) and it is supported by a powerful open-source community DIY (Do-It-Yourself).

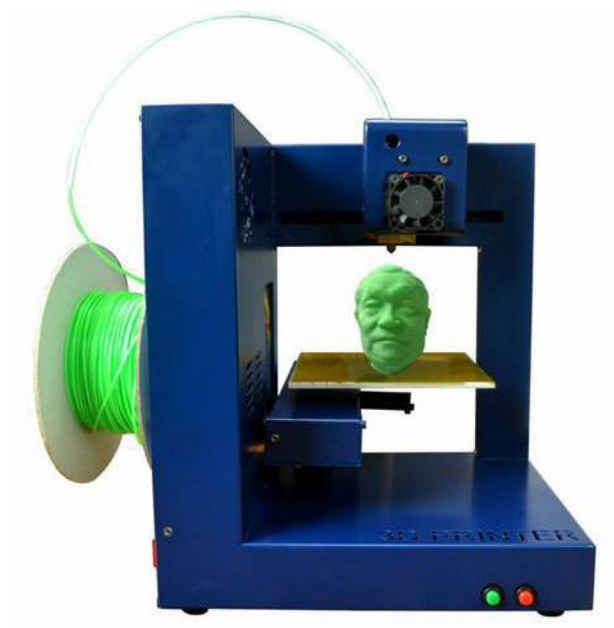


Figure 5. Cheap desktop FDM printer¹⁷

FDM processes can be used for quick making of models or prototypes for different purposes, or for manufacturing small series of products. DIW process applies “ink” directly onto a platform or a previously deposited material. In fact, the “ink” is a ceramic slurry with complex rheological properties, which, placed under pressure, when the velocity gradient is high, flows relatively easy (shear thinning), but when it is deposited and there is no velocity gradient, viscosity increases and the “ink” remains in place. The created object is not completely solid, and it must be dried or sintered. It is possible to combine ceramics with metal and to create objects of composite materials. DIW is especially appropriate for creating labware, lattices for filtration or catalysis, and artificial parts of the human body (bones).

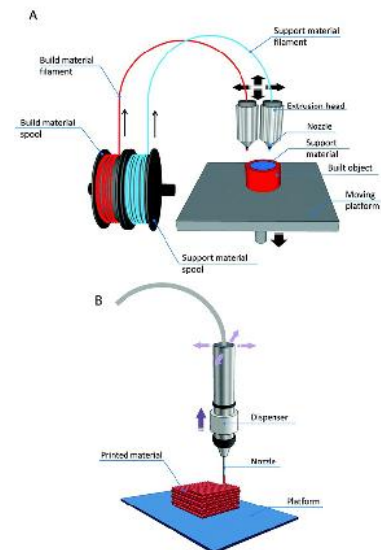


Fig. 6 Schematic representation of DIW¹⁸

Material Jetting

This process is similar to 2D ink jet printing. However, the ink layer is thicker and the platform carrying the objects can move in a vertical direction, so the 3D objects could be formed by a direct deposition of liquid material (ink). After depositing, material must be solidified by UV curing or by spontaneous drying. Material jetting can be divided into three subcategories:

- Liquid metal jet printing;
- Plastic jet printing;
- Multijet modelling (Fig. 7).

For a complex geometrical object, it is important to use support material, which is also applied by jetting.

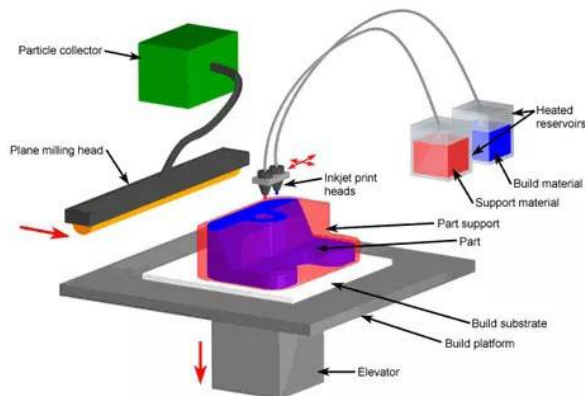


Figure 7. Schematic representation of multi jet modelling¹⁹

Material jetting technology is an excellent tool for a fast making of realistic and functional prototypes with fine details and precision. It is the most precise 3D printing technology today, up to 16-micron layers, which is thinner than a human hair. It is possible to use the following plastic materials: rigid opaque plastic, transparent plastic, rubber-like plastic, simulated polypropylene, heat resistant, simulated ABS.

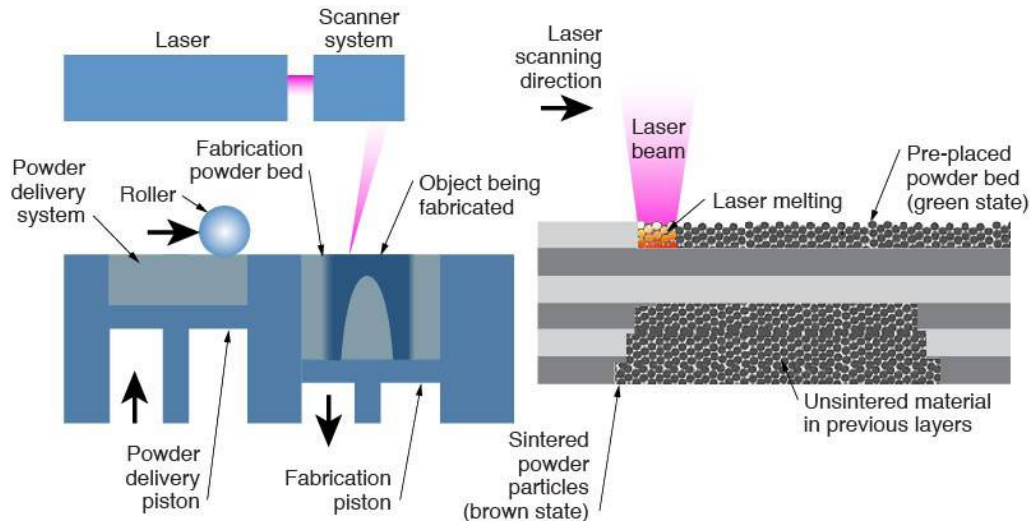


Figure 8. Schematic representation of SLM²⁰

Powder bed fusion technology is appropriate for producing functional prototypes and spare parts of complex geometry. The surrounding powder that is not melted or sintered provides an excellent support.

Sheet Lamination

It is also called "laminated object manufacturing" (LOM) or "selective deposition lamination" (SDL).

Powder Bed Fusion

The term powder bed fusion refers to processes based on selective heating of the powder layer.

Heating can cause melting or sintering, which makes the powder, exposed to heat, solid. There are many subcategories:

- Electron beam melting (EBM), for alloys including Titanium;
- Selective laser melting (SLM), for steel, Aluminum, Ti-alloys and Co-Cr alloys;
- Selective heat sintering (SHS), for thermoplastic powder;
- Selective Laser sintering (SLS), for thermoplastic or ceramic powder;
- Direct laser metal sintering (DMLS), for most of alloys.
- After heating one layer, the printing devices apply a new layer of powder. When the object is finished, the remaining powder is reused.

The process is based on successive lamination of the layers of the material and selective cutting of each layer.

After laminating and cutting the last layer, excess material, which is also cut, is removed and final 3D objects remain. Objects could be created out of preprinted foils of paper, metal or plastic, so it is possible to obtain coloured ones.

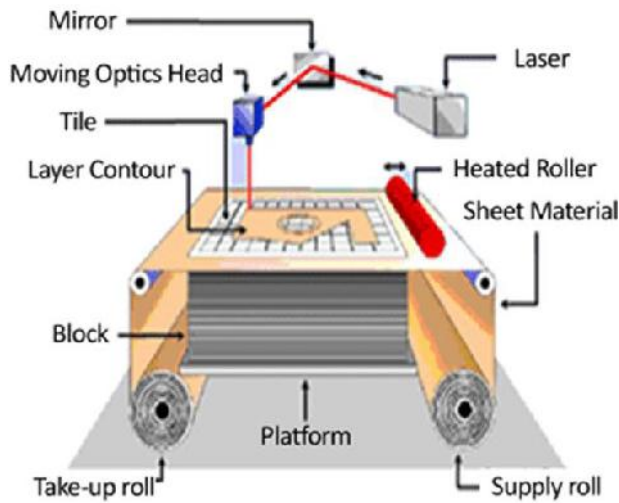


Figure 9. Schematic representation of LOM²¹

LOM processes are mostly used by artists, architects, and designers for making relatively large and cheap models and objects (fig. 10). Models have mechanical properties similar to wood. A disadvantage of this process is a relatively poor dimensional precision, in comparison to other 3D printing techniques.



Figure 10. Typical models created by LOM

VAT Photopolymerization

Vat photopolymerization refers to a few similar technologies:

- Stereolithography (SLA); this is the first 3D printing process; it utilizes a moving laser beam for curing the photopolymer;
- Digital light processing (DLP); it utilizes a micro mirror projector for curing the photopolymer;
- Continuous digital light processing (CDLP); polymer is cured by LED and oxygen;
- Continuous liquid interface production (CLIP).

Stereolithography works with liquid photopolymers. An object grows, layer by layer, in the container. A thin layer of photopolymer is cured by UV radiation and photopolymer becomes solid. Then a new amount of liquid photopolymer is added, to form a new layer to be selectively cured.

If UV radiation comes from above, the dimensions of the object are limited by the size of the container (fig. 11). However, if UV radiation comes from below, then it is possible to produce significantly larger objects (fig.12).

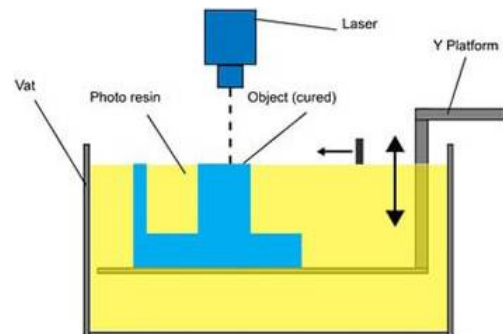


Figure 11. Schematic representation of VAT with approach from above²²

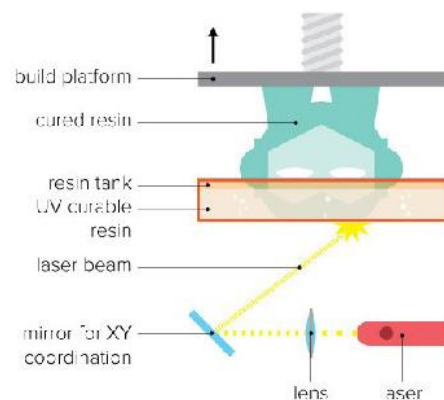


Figure 12. Schematic representation of SLA with approach from below²³

SLA is relatively fast technology for making larger objects that could have good mechanical properties. Accuracy and precision could be very high, comparing to other 3D printing technologies. SLA is appropriate for manufacturing models, highly detailed sculptures (fig. 13), spare parts and jewellery. The surface finish could be very smooth. However, the price of printers and polymers is still relatively high.



Figure 13. Highly detailed sculpture manufactured by SLA

Perspectives of 3D printing

The development of 3D printing technologies is somehow similar to developing desktop publishing technologies. It will enable a wide range of users with a different level of education to create 3D objects at home. On the other hand, industrial 3D printers are getting cheaper and more advanced, so the greater portion of machine parts industrial manufacturing will be 3D printed. Advancing 3D printing technology will open new fields of application in:

- Medicine (making prosthetics, artificial parts of the human and animal bodies, models for practising surgery);
- Designing machine parts (creating models and prototypes);
- Design and arts (making models, maquettes, decorative items);
- The analysis of problems (making maquettes and models).

There are authors that believe advancing 3D printing technology will:

- Help maintain a sustainable development in the world;
- Change the world economy because of new ways of production – production on demand;
- Making great developments in other fields possible;
- Even become the basis of a new industrial revolution.²⁴

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3D štampa – mogućnosti i perspektive

SAŽETAK

U ovom radu sistematizovana je klasifikacija postojećih postupaka 3D štampe, prikazan je princip rada svakog od postupaka, oblast primene, materijali koji se mogu koristiti, kao i neki ekonomski aspekti primene. Rad je preglednog tipa, zasnovan na informacijama dostupnim iz javnih izvora. U radu je predloženo i nekoliko primera praktične primene nekih od pomenutih postupaka.

Ključne riječi: 3D štampa, aditivna proizvodnja, desktop proizvodnja, proizvodnja na zahtev.