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ADDITIVE MANUFACTURING TECHNOLOGIES. A CONCISE INTRODUCTION

BY

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Abstract. The here described fabrication methods form together the so-called 3D Printing technology and have as a common purpose the building of a component, starting from nothing, by successively adding material layers, in a precisely controllable manner and following a 3D digital model made in advance. During the three decades since they appeared one after another on the market, seven basic methods have been developed, with more than 20 individual technologies which were derived from them, by many different industrial companies operating in the field. Among the main advantages of their use is the accurate building of complex parts, with no material waste and little or no post-processing, easy mass-customization of products, and the possibility of making objects difficult or impossible to achieve by classical methods. The AM techniques are used in very diverse and continuously expanding manufacturing applications, from consumer products to airspace and biomedical devices.

Keywords: 3D printing techniques; present; perspectives.

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1. Introduction

Generally speaking, the traditional manufacturing techniques (such as molding, casting and machining) are based on various types of technological operations that require the change of shape or the partial removal (subtraction) of material from the piece to be fabricated, with a limited ability to control the possible complex internal structure of that part. Over the last three decades, in contrast to classical techniques, a new important wide range of manufacturing methods has been spectacularly developed, on the principle of depositing (adding) the material, layer after layer, in order to build some component, following a pre-established pattern.

Certain similarities to the paper-based printing of texts and images have made the **additive manufacturing** (**AM**) methods to be globally called 3D printing; as a consequence, the machines that are used in those various types of processes are usually known as 3D printers. This paper represents a brief synthesis, based on recent literature in the field, on the current state of these manufacturing techniques and their prospects of widespread application on the world market.

2. Particular Aspects of Additive Manufacturing Methods

It is largely assumed that a patent obtained in the UK (Hull, 1986) was the starting point for the evolution of these techniques; it had as an object the method currently known as *stereolithography* (the first 3D printer, using this technique, was released by the same author in 1987) which will be discussed below, along with other basic categories of AM methods.

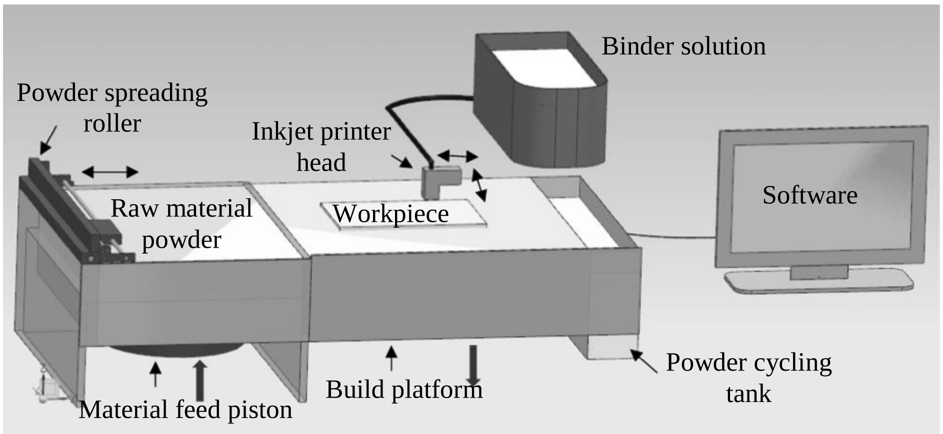

Fig. 1 – Basic principle of a 3D printing (BJ) process (Hwa *et al.*, 2017).

Following the extended application of these techniques, ASTM published (in 2009, reviewed in 2012) a document regarding the standard terminology on AM (ASTM F2792), establishing 3D printing as an industrial manufacturing technology. Its further development and diversification together with the steady establishment of its application principles led to the joint elaboration by ISO and ASTM of a comprehensive standard (ISO/ASTM 52900, 2015) on AM techniques. It is a fundamental document for the understanding and unitary description of 3D printing methods and is therefore used and cited by researchers around the world. With the development of the field, many other standards have been adopted in recent years (ISO/ASTM 52910/2017 and 52915/2016, for example), in order to normalize various particular aspects of these methods (Umaras and Tsuzuki, 2017).

The basic principle of additive manufacturing techniques (Fig. 1) is the realization of a new 3D object, starting from nothing, by depositing successive layers of material, on a suitable rigid support; the process is precisely controlled by following a computerized geometrical model (a digital stereolithography file format) of the manufactured object.

The model could be virtually built (Fig. 2) – the image on the left is a symbolic representation of a proposed porous material; it was modeled in a computer-assisted design (CAD) program, and then displayed – on the right side of Fig. 2, as a triangulated mesh, representing the graphical information (about the outer and inner surfaces of the object) in the so-called *Surface Tessellation* (or *Stereo Lithography*, or *Standard Triangulated*, in other versions) *Language* (**STL**) file – the industry standard file format for 3D printing. Alternatively, the digital model could be obtained by 3D scanning the real object to be made, using a layer-by-layer technique.

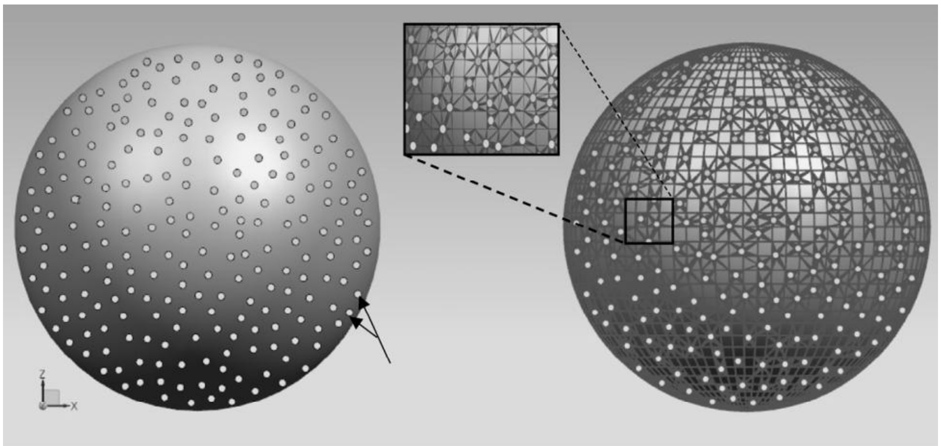

Fig. 2 – STL file for building a porous material object (Hwa *et al*., 2017).

It is important to observe that all modern CAD software is able to export the native file format into STL; the 3D model is afterwards converted into machine language through a process called *slicing*, and so it gets ready to be printed.

Selecting the optimal printing method can be difficult: the performance of a particular technology is quantified primarily by parameters such as fabrication accuracy, available volume and speed, functionality and cost of the product, strength and surface finish of the part.

3. Usual Printable Materials

Initial AM technological versions mainly used various polymers, but the range of 3D printable materials has expanded over the years so it currently includes metal alloys, various types of glass and ceramics, and also some advanced nanomaterials, biomaterials, functional or smart materials. These substances are used in various forms such as liquids, filaments, powders, or sheets. The results of applying printing techniques can be very different, from individual objects in multiple materials and colors, having a wide range of specific physical properties (ranging from optical clear to rubber-like objects), to interconnected moving parts (such as hinges or chain links) that are printed in a single operation.

3D printing not only can skip some traditional manufacturing steps, but can also reduce the wasted material and create objects that are difficult or impossible to produce with classical techniques, including components with complex internal structures that reduce weight, or increase functionality and strength. Some of the most spectacular current applications of these techniques use living cells (bioprinting) for creating organs for transplantation, containing internal networks of blood vessels.

From the polymers category, *thermoplastics* (more suited for structural applications) such as PA (polyamide), PC (polycarbonate), ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid), as well as *thermosetting* polymers like epoxy resins are usually processed by 3D printing technology (Khan *et al*., 2017). Epoxy resins are reactive materials that require thermal or UV curing to complete the polymerization process, so they are suitable for heat or UV-assisted printing process. Using various selections of materials, 3D printing of polymers has a wide range of possible applications in aerospace industries (for fabricating complex lightweight structures), education, architecture and art domains, but also in spectacular medical fields, for printing tissues and organs.

It is obvious that *metals* are used in 3D printing in applications that require materials with high values of strength, hardness or thermal resistance; their AM use is more and more extensive, with the statement that printed parts require careful topological optimization, for maximizing their performance and mitigate the high cost of the technology.

In the last decade, the advance in 3D printing towards the use of *ceramic* materials has broadened its application, making possible some new energy efficient, fast, and flexible approaches, with high resolution of fabrication (including some delicate details of the structure, such as pore size) and complex shapes. 3D printing can improve porous structure formation by controlling its microstructure and parameter optimization, and different sizes and styles of parts can be easily produced.

One may observe that additive manufacturing is a promising area to fabricate some complex porous ceramic objects such as 3D scaffolds, opening the possibility of tissue engineering of bones and skeletal structures that are tailored to the dimensions of the patient. On the other hand, based on their competitive thermal properties and relative strength, 3D printing of porous ceramics is also extensively used for catalysis, biomedical applications, heat exchangers and energy storage, filtration technologies and replacement automotive parts manufacturing.

4. The Seven Basic AM Techniques

It should be underlined that numerous (at least 20) AM technologies have been used during more than 30 years of their development, with important applications in automotive, aerospace, biomedical, architectural design, etc. An exponential increase in 3D printing technology was however observable in recent years and it continues to grow due to its versatility and low cost, combined with its customizability to build complex geometries, in monolithic structures, often with micrometer resolution. According to the above cited ISO/ASTM standard, seven broad categories of AM processes have been established, as it will be briefly described in the following paragraphs; the main techniques will be presented, for each of the categories, together with their particularities of application.

Binder Jetting (BJ)

Also named “Powder-liquid 3D printing”, this technique was developed quite early in 1993 by Massachusetts Institute of Technology (MIT), mainly for rapid prototyping. The material is used in powder form and can be very diverse in nature (usually metal, acrylic or even sandstone – from which very large parts can be built), as it does not need to be melted. The particles are simply joined together by selectively depositing on them (following the imposed pattern of the computerized model) a liquid adhesive agent that is dropped by the printing head (Fig. 1 from above), which is able to move in X-Y direction. The other work stages are practically found in all 3D printing processes: after each layer of the part is completed, the build platform is lowered on a distance of about 0.1 mm, then another powder layer is spread over the work surface, and the process is repeated; the unbounded powder is finally removed to get the printed part; at this stage it is very brittle, so additional post-processing is required.

It is an inexpensive and flexible technology with diverse applications, including parts with very complex geometries; the quality of final products is influenced by powder size, binder viscosity and deposition speed, together with the binder-powder interaction.

Material Extrusion (ME) / 3D Plotting (or **Direct Write)**

The polymeric material in a semi-molten (viscous) condition is pushed out (under a constant pressure) through a nozzle (movable in three dimensions), being deposited on the current layer of the build part (that is usually stationary), and so becoming rigidly bonded after solidification with the previously deposited substrate. Curing (solidifying) reactions can be induced by heat or UV light, or by dispensing some reactive components. Both material viscosity and deposition speed influence the quality of printed parts, which can also be controlled by altering such parameters as layer thickness, printing orientation, or raster width and angle. Flexibility of material appearance (solutions, pastes and hydrogels can be used) acts as the main advantage of the technique. On the other hand, since the raw viscous materials have low stiffness and cannot hold complex structures, a sacrificial material (such as polyvinyl alcohol) may be needed (being deposited simultaneously with the build material and later discarded) to support the printed part during building operation.

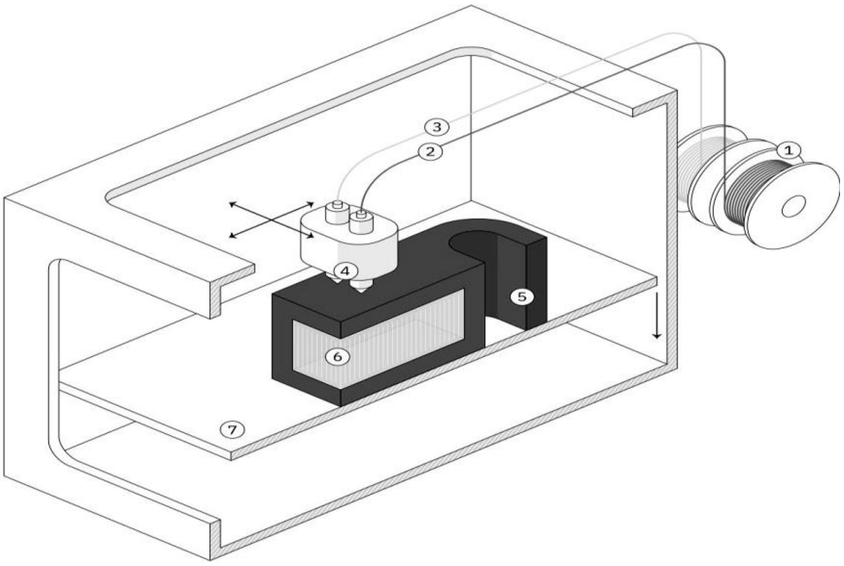

Fig. 3 – A typical FDM 3D printer: 1 – filament spools; 2 – main filament; 3 – support filament; 4 – extrusion head; 5 – printed part; 6 – support structure; 7 – build platform (https://best3dprinter.org).

The main variant of this technique (https://stratasys.com), which is using *thermoplastic* filaments (mainly plastic resin or wax) and is largely known as **FDM** (**Fused Deposition Modeling**) (Fig. 3) is currently the most largely applied AM technology. It is also the most cost-effective and has the shortest lead times (as fast as next-day-delivery), so is frequently used for prototyping and low-volume manufacturing of various custom components, including structural ones (for non-critical load). The careful control of nozzle temperature, scanning speed, and part cooling is essential for achieving high quality printed structures.

Material Jetting (MJ)

In a similar way to standard inkjet printing, a liquid (melted) polymeric material (of thermoset resins or photo-polymers categories) is continuously jet (as hundreds of tiny droplets), following the computerized model, on the current layer of the part (Fig. 4); the previous material layer is partially softened and then solidifies together with the new quantity of polymer. A support material is needed (and it is removed at the end of the process), in order to facilitate the correct building of the part. MJ is the most precise AM technology (with SLA/DLP being a close second), but also one of the most expensive, so it may be financially unviable for some applications.

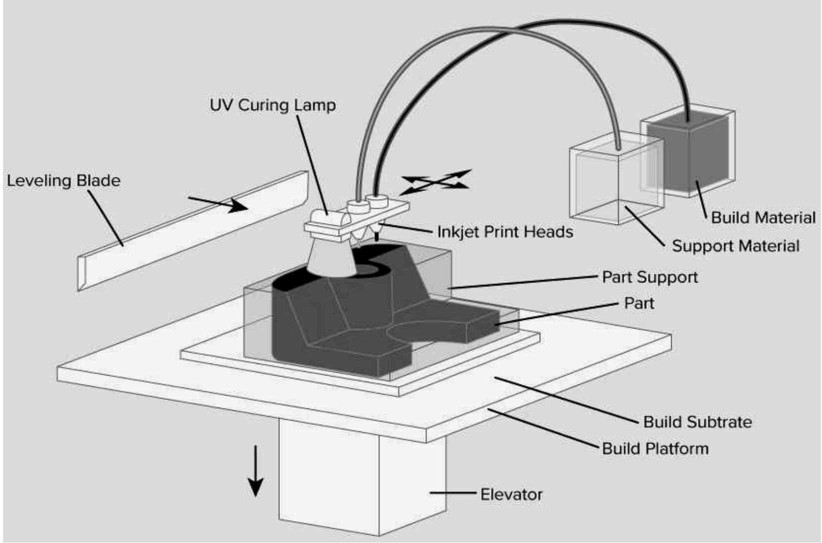

Fig. 4 – Schematic of Material Jetting process (https://3dhubs.com).

A spectacular variant of this method is the Inkjet-bioprinting: based on a technique which is also very similar to that of largely known inkjet printers, it is capable to build little organs and tissues (subsequently used as spare parts for human body) using human cell formations (grown from the patient's own tissues) as a raw material. The living cells are combined with a scaffolding material (usually a sugar-based hydrogel) and sprayed (following the computerized model) on the building platform, forming a tissue that is placed afterwards at suitable temperature and oxygen conditions for facilitating the cell growth and combination. At the end of these processes, the scaffolding material is removed and the printed tissue is ready for use.

Powder Bed Fusion (PBF)

A highly energized thermal source (such as a laser or an electronic beam) is used (Fig. 5), in order to *partially* (for a sintering process, used mainly for plastics) or respectively *fully* (for the melting binding mechanism) *melt* the material particles from the current layer that is placed on the printer platform. The particles strongly fuse together (and exhibit properties comparable to those of bulk material) in the **melt** state, but are bonded only at their surface (through molecular diffusion) – in the **solid-state sintering** (SSS) (because the temperature only exceeds the glass transition point of the particle material) – leading to an inherent porosity of the final part material structure. The fabrication parameters and the quality of the printed part are decisively influenced by an appropriate choice of thermal source power, scan speed and spacing, but also of particles binding mechanism; in addition, smaller powder particle sizes and thin layers are required to achieve finer details. At least three important groups of technologies are included in this manufacturing category, and they are briefly presented below.

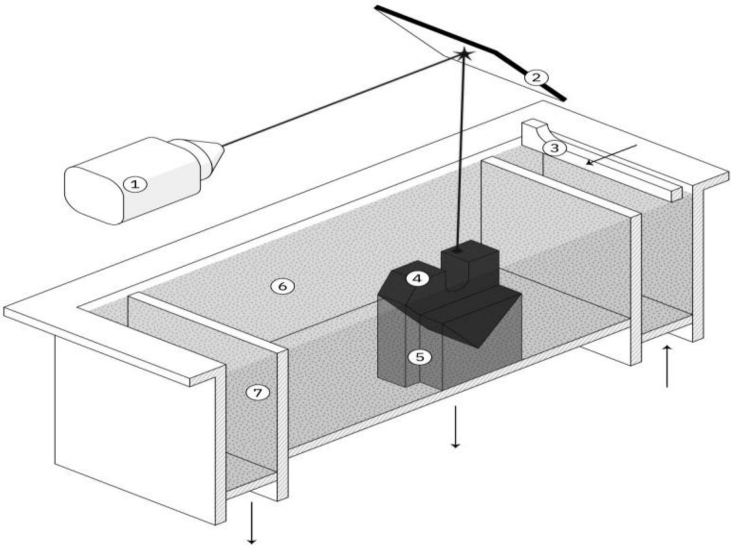

Fig. 5 – A typical DMLS 3D printer: 1 – laser; 2 – XY scanning mirror; 3 – recoater; 4 – printed part; 5 – support structure; 6 – powder bed; 7 – overflow bin (https://best3dprinter.org).

The **Selective Laser Sintering (SLS)** technique (https://3dsystems.com) involves complex consolidation and molecular diffusion processes, so it deals firstly with wax and other polymers, such as polyamide (PA) or (semi-) crystalline thermoplastics: polyethylene (PE), PEEK, and polycaprolactone (PCL); various ceramics and metals may also be used. SLS does not require any supporting structure, so it is capable to build complex components, with very good and almost isotropic mechanical properties, ideal for functional parts and prototypes. Moreover, it is suitable for small-to-medium batch production (up to 100 parts) because the raw particle bin can initially be filled throughout its volume and multiple parts can be printed at a single production run.

On the other hand, when using ceramic powders (that are characterized by high glass transition temperatures) the particles are coated with a thermoplastic polymer, which would melt first and fuse together. In this regard, SLS is a promising technique, especially for manufacturing tissue engineering scaffolds: as an example, some bone implants with good mechanical properties and regeneration potential have been fabricated from calcium phosphate and polymer particles; in addition, composites based on bioresorbable polymers and inorganic osteo-inductive materials have been used for creating 3D implants with structural gradients in material composition and porosity.

The other basic technological version **- Selective Laser Melting (SLM) -** leads to high density functional parts, and offer the possibility of manufacturing complex, high strength and net-shaped components with an appropriate preheating process. **Direct Metal Laser Sintering (DMLS)** is similar to SLS but it uses completely melted metal powder free of binder or fluxing agent, thus building a part with all of the desirable properties of the original metal material. DMLS is used for rapid tooling development, medical implants, and aerospace parts for high-heat applications (Han, 2017); DMLS/SLM parts have excellent physical properties, often surpassing the strength of rough metal; many metal alloys (or superalloys) that are difficult to process with other technologies are available with them.

On the other hand, **Electron Beam Melting (EBM)** (https://arcam.com) is an emerging technique that is not using a laser, but a high-power (up to 3kW) electron gun to heat powdered metal building parts layer by layer. An important particular issue is that many metal layers are melted simultaneously, instead of just the surface layer, leading to creation of stronger and more accurate parts. It is perfectly suitable, for example, in biomedicine, for rapidly and accurately building titanium custom implants, with no need of any post processing.

Direct Energy Deposition (DED)

Very close to the previous category, this method uses only *metal* powders (stainless steel, aluminum, copper, nickel or titanium) for printing operation, and brings together two basic technologies that are largely known as **Laser Engineering Net Shape (LENS)** and respectively **Electron Beam Additive Manufacturing (EBAM)**.

Sheet Lamination (SL)

Some material sheets (mainly of paper, plastic, fabrics or metals, but also synthetic materials and composites) are cut, using a laser (Fig. 6), and then bonded adhesively, thermally or by clamping – in **Laminated Object Manufacturing (LOM)** technique (an early version, on the market since 1991), or they are brought together using ultrasound – for **Ultrasonic Additive Manufacturing (UAM)** operation. The latest category is a *hybrid* one, because the AM process is usually combined with a subtractive manufacturing technique such as CNC milling. It is worth noting that any material sheet that is used in the lamination process represents a cross-sectional layer of the final part. Rapid tooling patterns and less detailed parts fabrication are usual objectives for LOM application; it must be observed that objects printed from paper material with this technique may have characteristics similar to wood, so being similarly worked through mechanical machining operations.

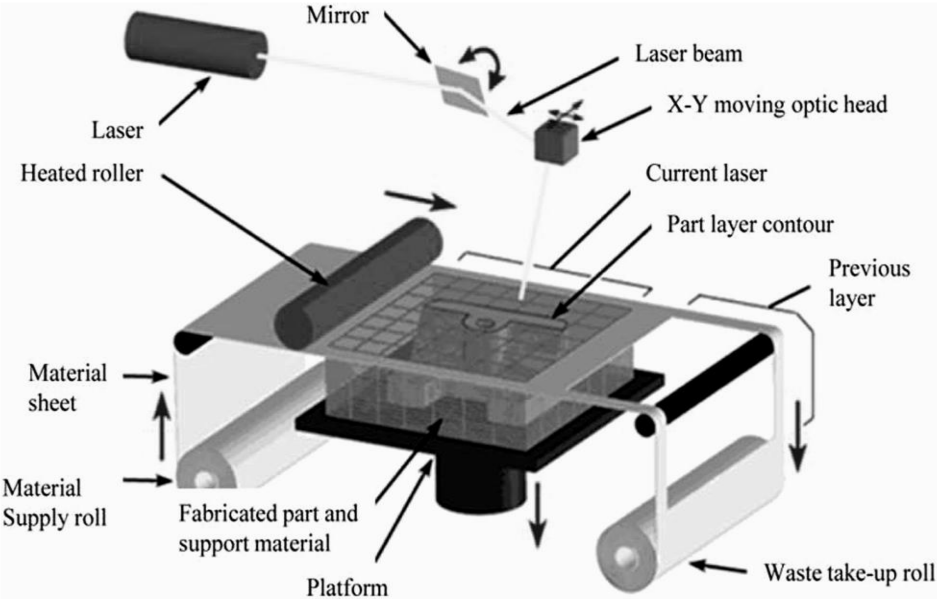

Fig. 6 – Schematic of Sheet Lamination process (Parandoush and Lin, 2017).

Vat Photopolymerization (VP)

The basic technique in this category is known as **Stereolithography (SLA)** (or solid imaging/solid free form fabrication); it is the specific variant that was the first patent subject in AM domain (Hull, 1986). A photo-polymerization process is a chemical reaction (favored by light beams action) of linking small monomers into chain-like polymers; the processed material is a reactive photo-curable (usually in the UV range) liquid resin that is exposed to a single-point UV laser (one 2D patterned layer at a time) and gradually solidifies. The other version of this method is **Digital Light Processing (DLP)**, which uses a digital light projector to flash a single image of each layer all at once. The reaction rate and depth are controlled by using complementary substances as catalysts (photo-initiators) and additives (UV absorbers).

Acrylic and epoxy resins are some typical polymer materials used in SLA; curing (solidifying) time and printing resolution can be adjusted by the right choice of laser power, scan speed and duration of exposure. Even from the moment of its invention, the SLA technique was used for rapid prototyping, but today it is preferred for creating parts with intricate shapes, at very high dimensional accuracy and high-quality finishes, such as jewelry.

5. Advantages and Drawbacks of AM Methods

As it was already outlined above, some general advantages are obvious for AM fabrication methods: rapid prototyping and manufacturing development, no need for specialized tooling (low start-up costs), geometric complexity (including complex internal shapes) with no extra cost, adaptability to various market factors, customability for each and every part, low volume of waste, combined with a high efficiency of material use.

As a matter of fact, with additive techniques several parts made of various materials can be replaced by one integrated assembly, which will reduce or eliminate cost, time and quality problems from assembling operations; a suitable redesign can result in an optimum strength-to-weight ratio able to meet functional requirements while minimizing material volume (Ford and Despeisse, 2016); as no excess material is wasted in AM, its use is particularly relevant for precious materials. Moreover, 3D printing may offer a simple way of instant robotic fabrication and ready-to-use functional systems. As another example, introduction of conductive substances for AM enables electronic circuitry to be built into the printed object. Consequently, full integration of the circuit into the accompanying object (so-called embedded electronics) becomes an important topic (Dilberoglu *et al*., 2017).

On the other hand, current limitations of 3D printing include relatively slow build speed, limited object strength, size, detail or resolution, possible anisotropic properties (and generally not as good as the bulk material), and high cost of raw and complementary materials (possibly including supports and their final removal).

An important and somewhat elusive limitation is that AM methods are less cost-competitive with traditional manufacturing technologies for higher fabrication volumes. The start-up costs are low, so prototypes and a small number of identical parts can be produced economically, but the unit price decreases only slightly at higher quantities: the turning point is assumed to be at around 100 units, depending on material, printing technique, and part design (https://3dhubs.com); after that, classical techniques as CNC machining and Injection molding are more cost effective.

Some supplementary issues have to be discussed, for example, when materials are supplied as powders (which is the case for many methods): characteristics such as particle size, shape and distribution will significantly influence the resulting structure and thus impact on the properties of printed part. The paragraphs below will detail that kind of aspects, referring to the main categories of techniques.

The advantages of BJ technique include free of support, room temperature processing environment, design freedom, flexibility of material selections, large build volume, high print speed, and relatively low cost. Some important drawbacks also exist: limited printing resolution, rough or grainy appearance, poor strength, post-processing required to remove moisture or improve strength, the presence of possible contaminants added by the binder.

The gains of DED method are: high deposition rate and material utilization; high efficiency for repair and add-on features; suitability for large components; deposition of thin layers wear resistant metals on components; low to medium part complexity. The poor quality of printing resolution, surface finish and dimensional accuracy are the main minuses of the technique.

Among the general benefits of PBF method one can note: high part complexity and wide range of materials; not support required for polymer powder; powders can be recycled. On the other hand, the rough surface finish for polymers; relatively low build rate; the possibility of building small to medium parts only; the use of some expensive machines appear as inconvenient aspects of that method. It must also be said, regarding all the *laser*-based techniques that they can be applied to a wide variety of materials, being ideal for metal parts with complex geometries (unmatched by traditional manufacturing methods), but the long and very expensive processes, together with the necessity of powders preheating act as inhibitors for largely expanding their use. More than that, part machining is often required to improve the accuracy of critical features (holes or other structural details), and a thermal treatment is necessary to eliminate the residual stresses (caused by extreme thermal gradients created by the very high process temperatures) in the part.

The ME techniques are versatile and easy to customize, with a variety of available aspects for raw materials. Among their minuses one can note the low level of precision, relatively long build time, possibility of nozzle clogging, inability to build sharp external corners, the visible layer lines on part surfaces, and the inherently anisotropic nature of printed components. An important disadvantage for FDM printers is the limited usable material – thermoplastic polymers with suitable melt viscosity (which are still forming a varied range of types). Also, it is difficult to completely remove the support structure of the part. Nevertheless, FDM printers offer advantages, including simplicity, low cost, high speed, but also the potential to allow deposition of diverse materials simultaneously, with multiple extrusion nozzles.

The MJ method is advantageous by high resolution; very high surface quality and dimensional accuracy (it is considered the most accurate form of 3D printing, because no heat is properly involved in the process); lack of material waste; possibility of multiple materials and colors. On the other side, the frequently necessary post-processing may damage thin and small features, and the support materials cannot be recycled, so becoming waste. Moreover, the method is based mainly on thermoset polymers, so the fabricated parts tend to be brittle, meaning no best suited for functional applications.

For the SL techniques some benefits are: high fabrication speed and surface finish; low material, machine, and process cost; no support structures needed; low warping and internal stresses (part heating is not required in the process); multiple materials and colors possible. Some important drawbacks are: high material waste; difficult to remove support trapped in internal cavities; possible warpage of lamination as a result of laser heat.

The main advantages of VP (SLA/DLP) printing technology are the ability to print parts with high resolution and accuracy, good surface finish; high fabrication speed; wide range of usable materials. Nevertheless, one can note as minuses the facts that it requires a support for build parts, and a post-processing to remove it, and also a post-curing stage for enhanced part strength. It is also noticeable that most of SLA parts must not be used outdoors, as their mechanical properties and colors may degrade when exposed to UV radiation. Finally, the high cost of the system, the inability of SLA to create compositional gradients along the horizontal planes, together with the possible long-time cytotoxicity of residual photoinitiator and uncured resin are important concerns for SLA industrial application.

6. Important New Categories of 3D-Printable Materials: AM Fabrication of Composites

At least three new important classes of materials are targeted to be produced on a large scale using AM technologies:

Electronic materials have possible applications in manufacturing functional components such as antenna, capacitors, resistors and inductors, usually in a single step technique and without any post-processing. For example, 3D printing may offer a simple way of instant robotic fabrication and ready-to-use functional systems. In this new era, introduction of conductive substances for AM enables electronic circuitry to be built into the printed object; consequently, full integration of the circuit into the accompanying object (so-called embedded electronics) becomes an important topic (Dilberoglu *et al.*, 2017).

Digital materials are advanced composites, combinations of photopolymers in specific microstructures and ratios, allowing for some physical and mechanical properties of the global material to be tunable, in certain limits; used for functional prototypes with adjustable physical features (Lee *et al*., 2017b), it also can simulate various elastomers, mimic standard plastics, producing photorealistic details for various applications (prototyping, tooling, medical models).

Biocompatible materials are used in 3D *bio-printing* of functional living tissues, which can be applied in regenerative medicine to address the needs for organs transplantation; the bio-printable materials range is for now very limited, mainly natural polymers and biocompatible synthetic polymers (Miao *et al*., 2017).

On the other hand, **ceramic** materials (including concrete) must also be brought in this discussion, because they are not suitable for 3D printing – their extremely high melting point is one of the most critical challenges in this field; some current AM methods can however produce ceramic components without any cracks or large pores and having similar mechanical properties to those of traditionally fabricated ceramics parts. Powder-based technologies are the most economical methods for ceramics, due to ease of parallel processing of multiple parts, manufacturing scalability and low cost of raw material. The 3D printed ceramic parts showed excellent thermal stability after *pyrolysis* at 1000°C and almost no shrinkage was observed (Hwa *et al*., 2017). These ceramics materials are of interest for thermal protection systems, propulsion components, electronic device packaging, micro-electromechanical systems, and porous burners.

An important challenge for this field is represented by **porous ceramics** manufacturing, because some severe technological requirements have to be met, mainly regarding the shape, dimension, and relative position of the pores in the ceramic structure, and possible also their interconnectivity. As a result, the main considerations in choosing the most suitable 3D printing technology are generally speed and cost of fabrication, materials selection, maximum resolution and accuracy, maximum dimensions of the porous part and minimum printing layer thickness; other criteria for assessment of each technique include surface quality, post-finishing, precision, resistance to impact, flexural strength, prototype cost and post cure requirements (to improve the parts' finish).

Another significant concern today, for 3D printing domain researchers is the use of AM methods for fabricating various types of **composite** materials; the starting idea for that kind of application was probably the real weakness of polymers, regarding the printed parts obtained on their basis. Polymer materials have usually low cost and weight, coupled with a good processing flexibility, so they are very suitable for AM processes, but the resulting objects are frequently deficient in mechanical strength and functionality as load-bearing parts. These problems can be solved by 3D printing of *polymer matrix composites*, so combining the properties of reinforcements with those of the base material, and obtaining new mechanical and functional characteristics non attainable by any of the constituents alone. The precisely computerized controlled microstructure of AM processed parts is very suitable for composites fabrication, so a good combination of process flexibility and high-performance products is possible.

The first stage of this development was the settlement of those composite materials categories that are compatible with the available 3D printers; the selection of a specific technique is based on the constituents' material, the speed and resolution requested for the process, and also on the cost and performance that are expected from the final product. Some pre-blended materials were firstly developed, with a wide range of **particles** (diverse in nature and size), but also of **nanomaterials** (metal and ceramic nanoparticles, carbon nanotubes and graphene) used as reinforcements, and on that way some 3D printed composites were obtained, having interesting mechanical, electrical and thermal properties. It is important to note that certain AM techniques (such as SL, SLS or FDM) are ideal to controllable deliver different volume fractions of nanomaterials to some specific areas of printed parts, so for fabricating *functionally graded* polymer **nanocomposites**, with optimized functional properties. In this regard, an interesting ultrasonic manipulation method was reported, to distribute glass microfibers in the resin matrix; the process shown a good versatility, leading to a variety of fiber orientation angles. This method is also used for fabrication of smart materials, such as resin-filled capsules for self-healing of polymers, or piezoelectric particles for energy harvesting.

Despite the cited achievements, it can still be assumed that **fiber** reinforcement remains the most attractive and effective filler for improving the mechanical properties of polymers. First attempts in this regard have been made using pre-blended materials including **discontinuous** fibers as an additive; it was found this way that some suitable properties of the final material can be obtained in an inexpensive manner. As a consequence, various fiber reinforced polymer composites are currently 3D printed by stereolithography (SL), laminated object manufacturing (LOM), fused deposition modeling (FDM), selective laser sintering (SLS), and extrusion (ME).

Fused deposition modeling is considered the most commonly used technique for fabricating polymer composites, having as basic materials thermoplastics such as PC, ABS and PLA, due to their low melting temperature. An inconvenient aspect of that method is the necessity for raw materials to be in a filament form to enable the extrusion process; the homogeneous dispersion of reinforcement and the minimization of voids in the final structure are difficult to be obtained in that case. Supplementary, the efficiency of discontinuous fiber reinforcements is limited due to fracture during mixing, random orientation, and un-even length of short fibers.

On the other hand, **continuous** fiber reinforcement is probably the biggest challenge, at present, for research in the field of AM fabricated polymer composites. It certainly offers significant improvement in mechanical properties, when comparing with discontinuous fibers, but insufficient progress has yet been made in this area, in order for some widespread manufacturing techniques to be established. Actually, numerous issues are still to be resolved in this field: composite heterogeneity, the negative effect of fibers on printing resolution, printer heads blockage, lack of adhesion for the constituents, and curing time increasing. An example of innovative technique is based on in-nozzle impregnation of continuous fiber (carbon fibers and twisted yarns of natural jute fibers) and thermoplastic matrix (Fig. 7): the resin filament and fiber are fed separately to the nozzle, where they are mixed and pre-heated, then ejected to the printing bed.

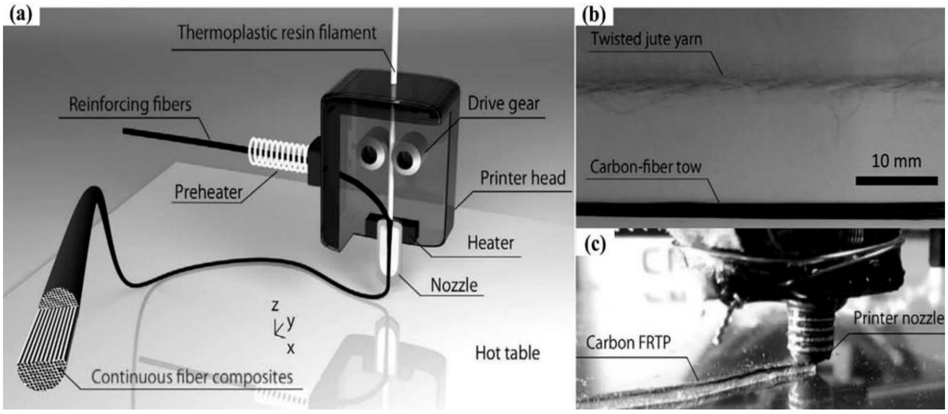

Fig. 7 – FDM printing of continuous fiber composites by in-nozzle impregnation: *a* – schematic; *b* – fiber bundles used in FDM; *c* – 3D printing process (Parandoush and Lin, 2017).

Another example (Wang *et al.*, 2017) of a pretty much used AM technique, is linked to some polymer composite panels (epoxy matrix with at least 50% volume content of unidirectional and continuous glass fibers) directly fabricated by LOM: the constituent materials are used in the form of commercial prepregs that are bonded in a vacuum thermoforming apparatus, and after the LOM process a post-consolidation cycle is applied, in order to increase the interface strength and reduce the void contents of composite structure.

Finally, it is worth shortly noting some aspects regarding the modeling and analytical techniques. Having in view that the microstructure of 3D printed parts often differs from that obtained by traditional manufacturing operations, a demand of suitable methods appears, for modeling and analysis of these structures. As an example, existing theories for short and continuous fiber composites need to be more or less modified, in order to be applied to various

AM produced composite parts; on its side, FEM remains a powerful tool to analyze any composite structure, and it can be applied for 3D printing domain with only slight modifications of existing finite element models.

7. 4D Printing Concept and its Materialization

It is largely known the existence of **smart** materials, a special category that is individualized by their capability of geometrically changing, under the influence of some external stimuli. **Shape memory** materials are important components of this class, having the inherent capacity to fix a temporary shape and then recover their permanent structure under suitable stimuli. On that basis, a spectacular emerging topic – **4D Printing** – has appeared in the field of AM technologies; its definition was firstly introduced in 2013, although the concept was already used previously.

Basically, it is about 3D printing of objects (usually from the smart composites category) that have the ability, right out of the printing bed, to gradually self-transform in shape or function under light, current, temperature change, or immersion into a solvent or even in water; as a consequence, **time** is assumed to be the fourth dimension of the multi-material printing process.

The precise placement of material at micro-scale during 3D printing of complex structures allows the implementation of programmable and computational materials in AM, in order to control the part condition after printing; as an usual example, the final construction can be manipulated to transform from one or two dimensional structures to 3D objects; that idea is applied in the design and fabrication of active origami, based on a flat sheet with active hinges that can fold into a 3D component. Some other interesting achievements are briefly exemplified in the following paragraphs.

Firstly, it must be noted that various combinations of constituent materials were used for obtaining different types of smart composites. Thereby, some thermo-mechanically programmable composites with complex shapes and a laminate structure were SLT printed using an elastomer as matrix and glassy polymer fibers as reinforcement. Another group of researchers reported the printing of some plant-inspired architectures, with a hydrogel composite ink, based on stiff cellulose fibrils embedded in a soft (acrylamide) matrix. The printing direction, together with the fibrils alignment makes the final structure programmable regarding its swelling upon immersion in water (Lee *et al*., 2017b).

Samples of water sensitive structures were made of two different materials with different water absorption capacities, being printed side-by-side in a sample. When putting the structure into a water bath, the water-absorbing material significantly increases (up to 150%) in volume, but the waterproof material remains unchanged, so the structure bends to its rigid side. Some hinges were designed having such a structure, and other shape transformation such as twisting and linear expansion can be achieved using suitable joint designs. It can be observed that, based on multi-material 3D printing technologies and anisotropic material compositions, the hygroscopic wood-type materials can be precisely programmed and manipulated to sense fluctuations in the environment and react through shape transformation.

Even more impressive results have been obtained by printing with some special nano inks (hydrogel liquid polymer containing some cellulosic nano-constituents); when the ink is extruded from the nozzle for printing operation, the shear stresses determine, for a fraction of the cellulose component to self-align in the hydrogel (similar to wood fibers structure); as a result, when the printed part is exposed to water, a noticeable anisotropic swelling of extruded fiber is produced, along the longitudinal direction (Fig. 8*a*).

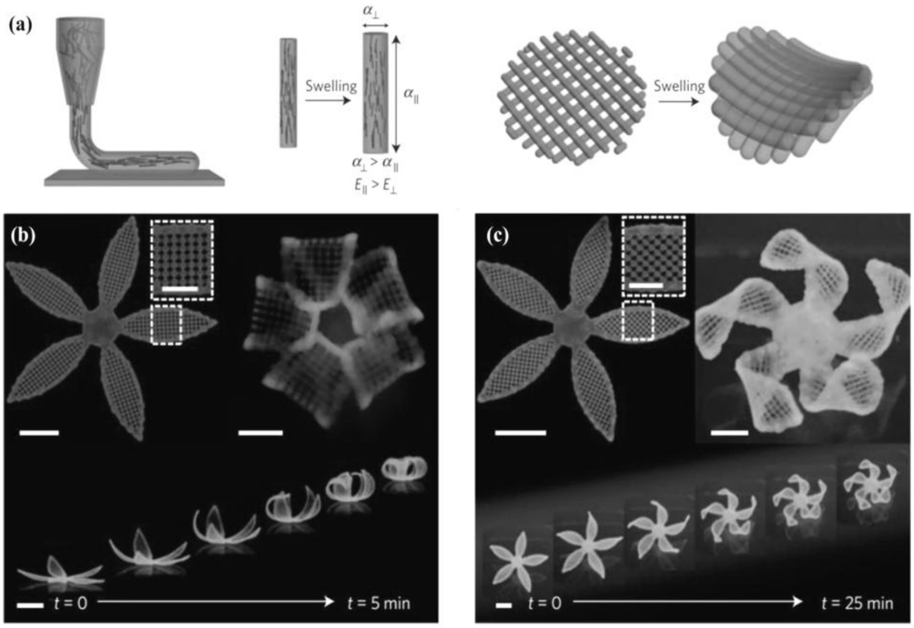

Fig. 8 – Biomimetic 4D printing of composite architectures (Parandoush and Lin, 2017).

That anisotropy results in a surprising behavior, for some structures built by super-imposing two anisotropic layers with different fiber orientations; it was reported that by controlling those layers combination one can predetermine the type of folding for the bilayered structures, when exposed to a wet environment. For example, in the case of a biomimetic construction with flower appearance, the petal structure with a 90°/0° angle arrangement evolves towards a closed flower shape (Fig. 8*b*), while a convoluted folding was observed, for the petals printed in a 45°/45° configuration (Fig. 8*c*). It is important to emphasize the possible development of these effects in designing and 4D printing a controlled reversible-shape-changing complex structure.

4D printing using shape memory polymers (SMPs)

Heat-activated SMPs are widely applied, because of their broad tunable range of mechanical, thermal, and optical properties. They also have a higher recoverable strain (up to 400%), when comparing to shape memory alloys (having just 8-12%). A permanent shape is set on the sample, by chemical or physical crosslinks induced in polymer structure; when the sample is heated above a certain temperature limit (the *melting*, or the *glass transition* point of the polymer) the molecular switching segments of the structure are soft enough to allow the sample deformation in the temporary shape; when the temperature drops below the limit, the segments solidify and immobilize the pre-designed temporary shape. The crosslink networks will return the structure back to its original shape, when the temperature rises again over the cited limit. It is important to note that, besides thermally initiated SMPs, a range of different materials having a time-dependent behavior are known, characterized by various shape fixation and shape recovery principles.

Shape memory thermoset polymers (which cannot be reshaped after their first solidification) can be directly printed with different techniques, such as extrusion, stereolithography (STL), direct laser printing (DLP) or UV curing of jet sprayed materials. Some adaptive hinge-type structures, capable of self-expanding and self-shrinking were printed (Miao *et al.*, 2017) using *digital* materials with adjustable values of glass transition temperature. The time-dependent behavior of each polymer allows the achievement of a temporal sequencing of activation, when a certain level of temperature is reached; as a result, various structures have been obtained, that rapidly respond to thermal stimuli by self-folding to specified shapes in a controlled shape-changing sequence (Fig. 9).

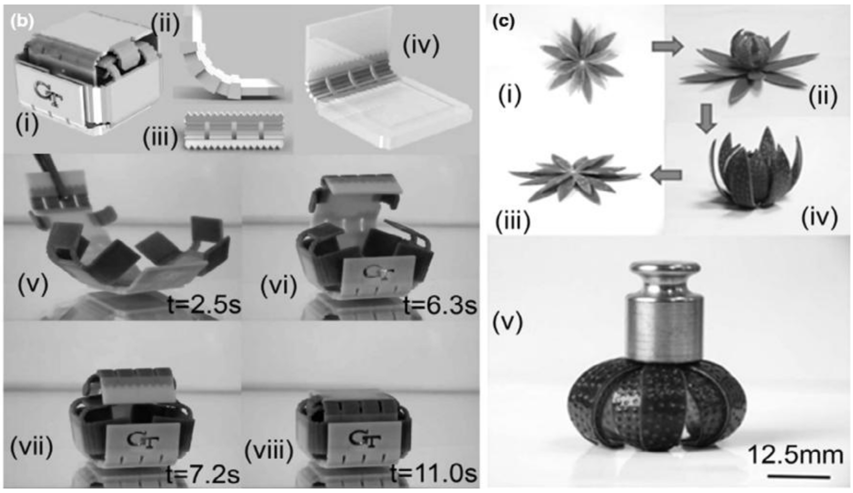

Fig. 9 – 3D printed shape memory folding structures (Miao *et al.*, 2017).

Switching to another example, some composite materials were reported, consisting of glassy SMP fibers that were directly printed in an elastomeric matrix, in precisely designed lamina and laminate architectures; after applying a suitable thermo-mechanical training process, a specific shape memory effect could be realized, allowing to a thin plate to transform into complex three-dimensional configurations such as coiled strips, folded shapes, or structures with non-uniform, spatially varying curvature. It is important that these objects will recover their original shape, when exposing to temperature rising.

A difficulty in using most thermoset polymers is their unprintability, so they must be combined with some sacrificial materials, such as poly lactic acid (PLA) and polyvinyl alcohol (PVA): the monomers for the polymers synthesis are poured into the mold, and after the curing process the sacrificial material is leached and the crosslinked thermoset 3D structure is left. That technique allows in particular the presence of a controllable, graded porosity in the printed part; some spectacular examples for this kind of achievements are the biomimetic and highly biocompatible gradient tissue scaffolds that were fabricated. The finely controlled printing process facilitates the achievement of various pore morphologies and physiologically appropriate printed structures.

On their side, the **shape memory thermoplastic polymers** (that can be remodeled because they become soft by heating) are readily used as printing raw materials; because compatible filaments are easily obtained by bulk material extrusion, they are capable to be used with FDM technology (the thermoset ones are not) which is cost effective and efficient. Though, the possible imperfect adhesion of the melt processed thermoplastic polymer strands can significantly affect the mechanical properties, mainly the toughness of the printed shape memory polymers. It is reported (Miao *et al*., 2017) that one can improve interlayer adhesion and strengthen the part by exposing the printed copolymer blends (that include some chemical compounds acting as radiation sensitizers) to an ionizing radiation (with gamma rays, for example), at a temperature close to the glass transition point of the shape memory system. That treatment facilitates the polymer crosslinking, enhancing the thermo-mechanical properties and solvent resistance of printed polymers; they possess partial characteristics of thermoset polymers without compromising the FDM printing process, and so it is possible to obtain inexpensive 3D printable parts that exhibit some good mechanical characteristics.

Novel processes and materials with great potential for 4D printing

Although in the preceding paragraphs various water-sensitive, humidity-sensitive, thermo-responsive and organic solvent sensitive materials were highlighted for achieving dynamic 4D phenomena, it must be noted that many other stimuliresponsive systems and processes (thermally-induced, or light triggered) also show great potential for being used in 4D printing techniques (Lee *et al*., 2017a). As an interesting example, multiple shape transformations, each controlled by a particular external stimulus, were achieved with a planar hydrogel sheet integrated with some small-scale polymer components with different compositions. Under the action of different stimuli (*i.e.* temperature, pH, or CO_2 supply), the structural components undergo differential swelling or shrinkage, causing internal stresses to appear within the composite hydrogel sheet. It must be noted that this model is physiological analogous to the complicated microenvironments in human body, containing multiple regulatory processes (humoral, neuro-, self-regulation, etc.), therefore multi responsive materials are notably suitable for biomedical applications.

8. The Current State of AM Methods Usage

a) Application for top industries

The 3D printing technology was initially developed for rapid prototyping in various industrial domains, but its use has now expanded into unexpected technical (and also non-technical) areas; the uses in leading industries are frequently cited, such as those briefly described below.

Some unconventional **electronic** devices have been reported, consisting of 3D printed polymer composites with electrically conductive reinforcements: combinations of carbon black and PCL, or of CNT (carbon nanotubes) and epoxy (forming a nanocomposite) were used for printing electronic sensors, both *piezoresistive* – able to sense mechanical flexing through the change of electrical resistances, or *capacitive* – embedded into smart vessels to indicate the presence of water in them (Lee *et al*., 2017b).

On the other hand, it is well known that most **aerospace** components have complex geometries, being time-consuming and very costly in fabrication, and AM technologies are highly suitable for designing, fabricating, and repairing them. As a matter of fact, the international space station has an AM machine for making parts and components in space (Tofail *et al*., 2018). For now, especially for equipment operating at high temperatures like engine exhaust and turbine blade 3D-printing with metal materials is used, since they are stronger and more flame retardant than polymers. Recently, the use of 3D printed polymer composites was investigated, in order to increase the fuel efficiency: for example, glass fiber and carbon fiber reinforced photopolymer composites were 3D printed, using a UV-assisted system, for airfoil and propeller fabrication, achieving high-fidelity replicas of digital models, excellent reproducibility and good mechanical properties of printed parts (Sossou *et al*., 2018).

An interesting new concept is *Print-in-Place* (PiP), the technique consisting in printing objects made of different and separated but “intertwisted” parts, so that relative displacements among these parts will be possible when the printing process is completed. The PiP systems, in fact, can incorporate several types of joints capable to inter-connect many moving parts. Moreover, the intrinsic additive nature of the process allows for generating these joints even in positions no longer accessible when the process is completed, generating mechanisms not realizable with the "conventional" manufacturing processes, which require part assembly. Moreover, an elastic element that connects the "rigid" parts can be manufactured directly in place, and the resulting joint will be "automatically" mounted during the manufacturing process, overcoming the need of designing complex assembly procedures (Rosa *et al*., 2017).

A recent phenomenon has also to be reported: AM is revolutionizing the **construction** sector, because structures with high complexity can be printed (even on site), including internal cavities and complications reproduced as single objects, with little to no waste materials (Ngo *et al*., 2018); in addition, a significant reduction in labor cost, together with an improved built quality are obtained, since the printing machines are extremely accurate and could technically work 24 h a day. It is largely assumed that the construction industry is responsible for consuming one-third of the Earth's resources, so material efficiency and effective construction strategies are important factors for addressing environmental impacts. The idea of 3D printing use for automated construction of buildings and infrastructure was firstly materialized with the development of **Contour Crafting (CC)** technique (Khoshnevis, 2004), a version of Material Extrusion method, using a mixture of cement and sand as material. Due to its ability to utilize in-situ materials, it can be readily used for constructing low-income housing, but also for building shelters on the moon, by using lunar soil. The first 3D printed residential structure was developed in Holland in 2014; during the same year an architectural firm in China mass printed residential houses in less than 24 h, by using cement and glass fiber as raw materials (Fig. 10), and a huge equipment – a 3D printer with a size of 150m×10m×6.6m (L×W×H) (Wu *et al*., 2016). Some problems such as structure brittleness and integration of building services are still to be solved, but the architectural application of 3D printing has already shown great potential.

a *b*

Fig. 10 – First 3D printed houses (*a*) in Holland and (*b*) in China (Ngo *et al*., 2018).

b) Spectacular development of printing machines

The 3D printing field has rapidly developed and continues to expand in impressive rates, this including the continuous progress (in printing resolution, accuracy control, and production speed) of machines that are used. Giant names from the classical printing industry have contributed greatly to the cited growth, together with various newcomers that have invented and marketed new versions of this category of techniques. As a consequence, it is assumed that as many as 10 different types of 3D printing machines are widely used on the world market today (https://best3dprinter.org).

In this connection, it is important to note that one of the world biggest companies (https://hp.com/go/3Dprint) has created and imposed on the market Multi Jet Fusion (MJF), a new 3D printing technique, on the Powder Bed Fusion type, and correspondingly a new class of printing machines, assumed today (https://medium.com/extreme-engineering) as one of the most versatile in the world. It was originally intended for work with plastics, and has now been adapted for metal 3D printing; the machine is distinguished by its high fabrication speed and extremely precise control of material deposition – the manufacturing process allows the adjustment of properties for practically each *volumetric pixel* (named **voxel** firstly by the same company, and now all around the world). The material platform for the machine is opened, so third parties are encouraged to get involved and innovate new materials, possibly never-before used in the field.

POWDER BED FUSION techniques

MJF Multi Jet Fusion	SLS Selective Laser Sintering	DMLS/SLS Direct Metal Laser Sintering / Selective Laser Melting	EBM Electron Beam Melting

Another big company (https://xjet3d.com) made an invention with a strong impact on the market – a completely new way of creating *metal* parts – the **Nano Particle Jetting (NPJ)** technology (included in the general Material Jetting, or Ink Jetting category); it lays down on the build platform (221 million drops per second) nano-particle of metal in ink form (*sub-micron* metal dust, kept in a liquid agent, that evaporate after deposition). The particles are then fused together by a heating element, at a temperature of up to 300°C, so the current printed layer is as fine as 1 micron in thickness. As a result, the waste of material is practically excluded, and the overall detail level and surface finishing requires no post machining or support removal processes. Supplementary, the operator safety is guaranteed, since the raw material is stored in sealed cartridges, and no residual metal dust can be inhaled or react to external elements (https://medium.com/extreme-engineering).

c) Biomedical application

3D printing is highly recommended for the biomedical field, mainly for engineering functional tissues and organs, because it involves a precise achievement of intricate structures, including those containing irregular pore sizes and distributions. With the development of Computed Tomograph (CT) and Magnetic Resonance Imaging (MRI) technology, three-dimensional images of patient specific tissues and organs have become more easily accessible, with higher resolution (Javaid and Haleem, 2017), and they are subsequently used for obtaining the computerized model of printed parts. The main substances currently used for printing are based on naturally derived polymers - gelatin, alginate, collagen, etc., or on synthetic polymer molecules - polyethylene glycol (PEG), poly lactic-co-glycolic acid (PLGA), polyvinyl alcohol (PVA), etc. The materials for biomedical applications have to be printable, biocompatible, with good mechanical and structural properties, but also having a good interaction with endogamous tissues.

In tissue engineering, scaffolds are critical to provide a physical connection for cell infiltration and proliferation. Printing of biodegradable and biocompatible composite scaffolds was achieved by adding bioactive particles into polymers. On the other hand, *biofabrication* (*bioprinting*) of living organs using living cells for tissue and organ transplantation are the new challenge for 3D printed polymer composite applications in the biomedical industry. Several types of tissues and organs, such as ears, vasculatures, aortic valves, or cartilage and liver tissue constructs have already been successfully printed to meet the basic requirement for transplantation, so this category of techniques has long-term potential to save or extend many lives.

Amongst the 3D printing methods, SLA has become a strong prospective technique for biomedical engineering, and it can be used to fabricate customized scaffolds with strong support cell attachment and better surface finish. It can be easily combined with MRI and CT imaging techniques, facilitating the achievement of specifically designed vital medical devices. SLS and SLM are other frequently used AM techniques (despite their limitations, due to the high fabrication temperatures), which can produce complex ceramic structures, including 3D printing for bone tissue scaffold applications that can promote some healing mechanisms for bone defect. It must also be noted that the molten particles are attached to the build surface and increase the roughness, so this surface structure usually requires post-machining. In SLM, on the other hand, the complexity of a component has a low effect on the unit costs, because the costs of that process are more influenced by the volume, than the actual geometry of printed parts.

d) Application of 4D printing in tissue and organ regeneration

Based on all the advanced characteristics of AM techniques, 4D printing combines the merits of additive manufacturing and smart materials; it encloses a time-dependent dynamic process in the design and fabrication of some complex structures, with multiple communicating compartments and dynamic shape changing capabilities, so being more analogous to living organisms. That resemblance could be enhanced by adding the ability to synthesize protein from encapsulated DNA, using an in vitro system which is controllable by external light. The obtained synthetic tissues have great potential for use in drug delivery and tissue replacement surgeries. On the other hand, the shape memory effect of the fabricated scaffolds allows for their autonomous deployment in otherwise inaccessible places. For example, a polymer shape memory tracheal stent was printed based on anatomical data; it can be deformed into its temporary shape, inserted in the body and then deployed back into its permanent shape with a local increase in temperature. Other reported studies have shown the great application potential of 4D devices which adapt to growing or changing tissues, particularly for pediatric applications. It must be emphasized that the synthesis and development of 4D inks requires a high level of expertise and significant effort: specific to tissue and organ engineering applications, it is compulsory for the printing materials to be biocompatible (and often also biodegradable) and capable of performing dynamic 4D processes in physiological environments.

e) The role of the internet in expanding AM application

It is easy to assume that AM technologies are considered very promising for the immediate future, including because they render very low volume production economical, and so enable mass-customization on a very large scale; they also create unprecedented opportunities for co-creation between firms and their customers, based on the link between the two parts that the Internet represents. At this aim, several (they are over 20, when counting only the very active ones) online 3D printing platforms have appeared over the past decade; just like Web 2.0 and social media, their enable firms and users to engage in co-creation activities, having the potential to be significant vectors of user innovation (Rayna *et al.*, 2015). There are countless domains of human activities for which the Internet increased the users' participation in the production process: the content provided by users accounts for most of the service value, so users are no longer pure consumers, but rather *prosumers* (a modern business term meaning "production by consumers").

Therefore, online printing platforms enable a wide range of user involvement in the production process, from buying a set design that is printed and delivered by the platform, to the highest participation level – the customer codesigns the object and prints it at home. By providing customers with easy to use and effective means of productions, recent technological progress has empowered consumers with the ability of initiating their transformation to prosumers; more than that, most online 3D printing platforms already provide significant means for them to take advantage of other consumers' innovations.

9. Estimated Prospects for the Future AM Methods Development

It is very interesting to observe that the wide spread of AM use, in the three decades since its appearance, evolved from rapid prototyping (1980s), to rapid tooling (1990s), and then to Direct Digital Manufacturing (2000s), with end-products directly fabricated using digital models and 3D printers. It is largely assumed that the fourth and final stage of adoption – home fabrication – has just started. On the other hand, one of the key aspects of 3D printing technologies is that they enable to rapidly change and experiment with business models, creating new opportunities as well as challenges; market structure is now more dynamic and key boundaries that used to exist tend to progressively disappear (consumers are becoming producers, niche market is becoming attractive to large players, and so on) (Rayna and Striukova, 2016).

Regarded as the trigger of a new industrial revolution (Dilberoglu *et al*., 2017), 3D printers are already largely used for creating product designs and prototypes, but also for direct production of tools, molds or even final products; some unprecedented levels of mass customization are expected (including better fit for items such as shoes), together with a contraction and reduction in the costs of transportation, assembly and distribution chains, and even a "democratization" of manufacturing, because many consumers and entrepreneurs begin to print their own products. A wide range of very different products are fabricated using AM techniques, from parts of airspace vehicles and iPhone cases to dental prostheses and organs for transplantation (printed with the patient's own cells). Generally speaking, the materials used in 3D printing are still quite expensive, but prices are declining rapidly as the production volumes increase; in addition, new types of materials have been adapted for additive manufacturing every year. The databases cited in literature currently list over 800 materials that are considered 3D printable today; many of these are however dedicated to specific types of commercial equipment, so the options for mass production are still pretty limited.

For the consumer product domain, certain categories such as toys, fashion and tech accessories, jewelry, footwear or ceramics are expected to be strongly influenced by developments in this area, because they are easily printable products, having high customization value for consumers; it is estimated that in less than ten years from now on most, if not all, consumers of these products could have access to 3D printing (direct product manufacturing) - with their own printing machine, or using a printer in a local store, or ordering 3D-printed products online. As a consequence, a massive increase in printing capacity becomes necessary, together with commercial 3D printing machines that have to be bigger, better, faster, and much cheaper to operate.

All these will possibly result in access to products that aren't otherwise available, but also in significant spending cuts for consumers, coming not only from eliminating the costs of whole sale and retail distribution, but also from reducing the costs of design and advertising embedded in the price of products. In terms of printed products design, it will partially be provided for payment to consumers, but probably many free designs will be available online (including through exchanges between users). More of the rest will come from new technologies like augmented and virtual reality, and many may also come directly from 3D scanning of real objects (https://mckinsey.com).

The prospective success of 3D printing depends to a considerable extent on reducing the materials cost, but also on improvements in build speed, mechanical properties and surface quality of printed parts, 3D scanners, and supporting software applications. Regarding the costs and performances of printing machines, it is estimated that the expiration of key patents for printing technologies (that is taking place today) could help to spread free software and encourage rapid innovation, and so determining the development of some low-cost, highly capable 3D printers for businesses and consumers. As an illustrative example, the patents on FDM expired in 2009, and consequently the first *desktop* 3D printers, with low cost (some prices were reduced even 100 times), were marketed (https://3dhubs.com).

It is also interesting to note that the emergence of new process innovations (such as AM techniques) makes it possible to locate the manufacturing in relatively high labor-costs regions, and the ability to meet the new trend toward mass-customized production makes it an attractive option for western companies to employ (Kianian *et al.*, 2015). Moreover, there would be more need for high-skilled labor to operate with advanced machinery like 3D printers. It is also assumed that AM technologies foster job creation both in product development stages (*e.g.* rapid prototyping), and in manufacturing stages of low-volume batches, mostly for complex design products (as it is the case with aerospace industry).

On the other hand, the spread of 3D printing appliance creates opportunities for better economic and social life of the people in both advanced and developing countries: important benefits can be brought for societies from mass production with less waste and less requirements for transport over long distances, so with less negative impact on the environment. The leaders of these countries should therefore be interested in funding research in 3D printing technologies, but also in ensuring appropriate intellectual property protections in this comprehensive field (Jiang *et al.*, 2017). One must say that some possible ethical risks cannot be neglected: for example, the world has learned from the media that 3D printers have already been used to make handguns. Societies have to evaluate and address these risks without limiting the value that these manufacturing techniques can provide.

10. Conclusions

3D printing is currently largely considered as a turning point for manufacturing techniques. The potential of precisely fabricating functional devices, directly from commercial 3D printers, and with controllable properties, has led to widespread recognition of the strong impact in today's world of AM techniques. As a consequence, the application of these methods is expanding, unsurprisingly, in more and more areas, from the top industries, robotics, and biomedical science to the consumer goods domain. For example, AM of composite materials enables precise control of physical, electrochemical, thermal, and optical properties of printed parts; moreover, these structures can even transform their shape over time in 4D printing. As an important emergent issue in this field, 4D printing has shown great application potential and continues to generate attention; its development still requires technological advances in software, modeling, mechanics and chemistry. As a fundamental concern, the design and achievement of multi-responsive structures triggered by various stimuli must attract further significant efforts and expertise.

One of the major advantages of 3D printing is fabrication of customized parts, in unique configurations and in very small quantities. The use of the internet brings with it the possibilities of design sharing and modifications, so the target component can be printed anywhere. Due to the enhancements in detail, precision and surface finish, 3D printing has been progressively used for medical applications, such as the fabrication of individual porous scaffold (resembling natural bone structure) for tissue engineering.

Into another field that is strongly influenced by these highly customizable techniques, the problem of porous ceramic manufacturing gets new and interesting approaches for various applications as surgical tools, patient specific prostheses, scaffolds, dental porcelain and porous ceramic filter fabrication. When comparing with the classical technological methods, the introduction of 3D printing technology increases flexibility, repeatability and speed, facilitates fabrication of fully interconnected and controllable pore networks, eliminates tooling constraints, requires low cost investments and enables sustainability of the fabrication process.

Some predictable advancement in interlayer adhesion of printed structures, dimensional stability, surface finish and resolution will be advantageous for 3D printing progress, especially in the micro- and nano-fabrication fields. Advances must also include improvement in the performance of additive manufacturing machinery, an expanding range of printable materials, together with lower prices for both printers and raw materials. It can be understood that achieving these objectives must be based on continuous efforts and on well-balanced investments in people, processes and technology.

REFERENCES

Dilberoglu U.M., Gharehpapagh B., Yaman U., Dolen M., *The Role of Additive Manufacturing in the Era of Industry 4.0*, Procedia Manufacturing, **11**, 545-554 (2017).

Ford S., Despeisse M., *Additive Manufacturing and Sustainability: an Exploratory Study of the Advantages and Challenges*, Journal of Cleaner Production, **137**, 1573-1587 (2016).

Han P., *Additive Design and Manufacturing of Jet Engine Parts*, Engineering, **3**, 648-652 (2017).

Hull C.W., *Apparatus for Production of Three-Dimensional Objects by Stereolithography*, Google Patents (1986).

Hwa L.C., Srithar R., Alias M.N., Norhayati A., Uday M.B., *Recent Advances in 3D Printing of Porous Ceramics: A Review*, Current Opinion in Solid State and Materials Science, **21**, 323-347 (2017).

Javaid M., Haleem A., *Additive Manufacturing Applications in Medical Cases: A Literature Based Review*, Alex J. Med. (Alexandria Journal of Medicine), https://doi.org/10.1016/j.ajme.2017.09.003 (2017).

Jiang R., Kleer R., Piller F.T., *Predicting the Future of Additive Manufacturing: A Delphi Study on Economic and Societal Implications of 3D Printing for 2030*, Technological Forecasting & Social Change, **117**, 84-97 (2017).

Khan I., Mateus A., Kamma Lorger C.S., Mitchell G.R., *Part Specific Applications of Additive Manufacturing*, Procedia Manufacturing, **12**, 89-95 (2017).

Kianian B., Tavassoli S., Larsson T.C., *The Role of Additive Manufacturing Technology in Job Creation: An Exploratory Case Study of Suppliers of Additive Manufacturing in Sweden*, Procedia CIRP (12th Global Conference on Sustainable Manufacturing), **26**, 93-98 (2015).

Khoshnevis B., *Automated Construction by Contour Crafting - Related Robotics and Information Technologies*, Autom. ConStruct, **13**, *1*, 5-19 (2004).

Lee A.Y., An J., Chua C.K., *Two-Way 4D Printing: A Review on the Reversibility of 3D-Printed Shape Memory Materials*, Engineering, **3**, 663-674 (2017a).

Lee J.-Y., An J., Chua C.K., *Fundamentals and Applications of 3D Printing for Novel Materials*, Applied Materials Today, **7**, 120-133 (2017b).

Miao S., Castro N., Nowicki M., Xia L., Cui H., Zhou X., Zhu W., Lee S., Sarkar K., Vozzi G., Tabata Y., Fisher J., Zhang L.G., *4D Printing of Polymeric Materials for Tissue and Organ Regeneration*, Materials Today, **20**, *10*, 577-591 (2017).

Ngo T.D., Kashani A., Imbalzano G., Nguyen K.T.Q., Hui D., *Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges*, Composites, Part B, **143**, 172-196 (2018).

Parandoush P., Lin D., *A Review on Additive Manufacturing of Polymer-Fiber Composites*, Composite Structures, **182**, 36-53 (2017).

Rayna T., Striukova L., Darlington J., *Co-Creation and User Innovation: The Role of online 3D Printing Platforms*, Journal of Engineering and Technology Management, **37**, 90-102 (2015).

Rayna T., Striukova L., *From Rapid Prototyping to Home Fabrication: How 3D Printing is Changing Business Model Innovation*, Technological Forecasting & Social Change, **102**, 214-224 (2016).

Rosa F., Bordegoni M., Dentelli A., Sanzone A., Sotgiu A., *Print-in-Place of Interconnected Deformable and Rigid Parts of Articulated Systems*, Procedia Manufacturing, **11**, 555-562 (2017).

Sossou G., Demoly F., Montavon G., Gomes S., *An Additive Manufacturing Oriented Design Approach to Mechanical Assemblies*, Journal of Computational Design and Engineering, **5**, 3-18 (2018).

Tofail S.A.M., Koumoulos E.P., Bandyopadhyay A., Bose S., O'Donoghue L., Charitidis C., *Additive Manufacturing: Scientific and Technological Challenges, Market Uptake and Opportunities*, Materials Today, **21**, *1*, 22-37 (2018).

Umaras E., Tsuzuki M., *Additive Manufacturing - Considerations on Geometric Accuracy and Factors of Influence*, IFAC PapersOnLine (International Federation of Automatic Control), **50**, *1*, 14940-14945 (2017).

Wang X., Jiang M., Zhou Z., Gou J., Hui D., *3D Printing of Polymer Matrix Composites: A Review and Prospective*, Composites Part B, **110**, 442-458 (2017).

Wu P., Wang J., Wang X., *A Critical Review of the Use of 3-D Printing in the Construction Industry*, Autom. ConStruct, **68**, *1*, 21-31 (2016).

*** ASTM F2792, *Standard Terminology for Additive Manufacturing Technologies*, ASTM International (2012).

*** ISO/ASTM 52900, *Additive Manufacturing General Principles-Terminology* (2015).

*** ISO/ASTM 52910 (E), *Standard Guidelines for Design for Additive Manufacturing* (2017).

*** ISO/ASTM 52915, *Standard Specification for Additive Manufacturing File Format* (2016).

https://mckinsey.com, McKinsey Global Institute, *Disruptive Technologies: Advances that will Transform Life, Business, and the Global Economy* (2012).

https://medium.com/extreme-engineering, *Three Additive-Manufacturing Technologies to Watch out for in 2017* (2016).

https://arcam.com

https://best3dprinter.org

https://hp.com/go/3Dprint

https://stratasys.com

https://xjet3d.com

https://3dhubs.com

https://3dsystems.com

TEHNOLOGII DE FABRICARE PRIN ADIŢIE DE MATERIAL. SCURTĂ INTRODUCERE

(Rezumat)

Spre deosebire de metodele clasice de fabricare, cele descrise în lucrare se bazează pe construirea pieselor prin adăugarea de material, strat peste strat, urmând trasee precise, care sunt preluate automat de pe un model digital tri-dimensional realizat în prealabil. Asemănarea de principiu cu tipărirea pe hârtie a condus la răspândirea

denumirii globale de Imprimare 3D pentru aceste tehnologii. De-a lungul celor trei decenii de la apariţie au fost dezvoltate şapte tehnici de bază, ale căror variante se multiplică pe măsură ce se adaptează la folosirea unor materiale noi şi la domenii noi de utilizare, care deja sunt foarte diverse, de la domeniul casnic la industria aerospaţială şi la bio-medicină. Principalele beneficii pe care le aduc sunt realizarea precisă a unor piese complexe, de obicei fără prelucrări suplimentare, eliminarea risipei de material, personalizarea uşoară a produselor la cerinţele clienţilor. Pentru moment costurile relativ mari de producţie şi durata de fabricare mai mare ca la tehnologiile uzuale apar ca dezvantaje importante.