Chapter 5

Advanced Technologies in Manufacturing 3D-Layered Structures for Defense and Aerospace

Dionysios E. Mouzakis

Additional information is available at the end of the chapter

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Abstract

In the past 20 years, a great progress has been made in additive manufacturing techniques, which has led to numerous applications in aeronautical and defense structures. Though not all advanced materials and alloys, can be automatically layered by a rapid prototyping system or machine, several interesting application have seen the light of publicity in many sectors. Efforts are underway to apply the automated layering technologies in as many materials as possible, mostly nowadays plastics, reinforced-polymers, and metals can be processed by such systems in order to produce three-dimensional parts. The work is underway internationally in order to promote more and more applications of additive manufacturing or automated layering and to lower the costs in such systems. This paper aims at presenting a review of the additive manufacturing history presenting the major steps that lead to the explosion of this technology, and with a special focus on advanced 3D structures in aerospace and defense applications. An insight is also given on the four dimensions of manufacturing concept.

Keywords: laminated manufacturing, 3D printing, rapid prototyping, additive manufacturing

1. Early research and development of making 3D objects

It was back in the late 1960s, when the creation of solid objects using photopolymerized resins was attempted, by employing a laser. The attempt took place at the Battelle Memorial Institute in Columbus, Ohio, USA [1]. During this pioneering experiment, two laser beams with non-similar wavelengths were pointed to intersect in the middle of a transparent container filled with of resin. Inside the vat of resin (usual term nowadays), the polymer crosslinked and solidified at the point where the laser beams intersected. DuPont had already made available the photopolymerization of resins as a technology in the 1950s. Quite similar to this approach, Swainson filed a patent titled "*Method of Producing a 3D Figure by Holography*" in Denmark, in 1967. His procedure was also based on dual-laser beam scheme. From 1967 to 1994, the laser-induced photopolymerization was being developed, but until then no functional 3D printer was offered to the market. In the early 1970s, a company called Formigraphic Engine Co., applied the dual-laser intersection paten, aiming at the first commercially available laser-prototyping machine. At that time, they coded the methodology under the term "photochemical machining." That company, however, succeeded to present the creation of a 3D object in 1974. Later, Formigraphic became Omtec Replication, and led the development of similar techniques with the help of DARPA funding. As the decade expired, a number of patents regarding solid photography were claimed by Dynell Electronics Corp. Their invention described the cutting of cross sections, in any soft material available, usually carton or plastic, using either a milling machine or laser, guided by computer control and stacking the sections sequentially, to form a 3D object. Nowadays, the technique is called laminated object manufacturing (LOM). Dynell merged with United Technologies Corp. in 1977. Their merger was independent and was called Solid Photography. This company opened an affiliated retail outlet named Sculpture, which by mid-1981 had changed its name to Robotic Vision.

1.1. Stereolithography emerges

According to many sources, Hideo Kodama, working at the Nagoya Municipal Industrial Research Institute (Nagoya, Japan), was one of the first to invent the single-beam laser curing approach, In mid-1980, he filed a patent in Japan, which unfortunately expired without proceeding to the examination stage, this being a requirement of the Japanese patent application procedure. Kodama apparently had obstacles in securing funds for additional research and development. In 1981, he published a paper titled "*A Scheme for Three Dimensional Display by Automatic Fabrication of Three Dimensional Model*" [2] and another paper titled "*Automatic Method for Fabricating a Three-Dimensional Plastic Model With Photo-Hardening Polymer*" that outlined his work in detail and offering thus the technology openly to the public [3]. During his experiments, UV rays were projected, using a mercury lamp, (Toshiba) into a photosensitive-photopolymerizing resin called Tevistar® produced by Teijin. In Kodama's innovating technique, black and white film was used to mask and accurately determine the region of exposure to UV light, and thus to define each cross section. His first paper also described the application of an x-y plotter device and the use of optical fibers as carriers of UV light. His approach was used by CMET Company in the SOUP 530, 600, and 850 stereolithographic systems. In his paper, Kodama quotes, "*If the solidified layer is immersed into the liquid with the top at a depth equal to the thickness of the layer to be solidified, its top surface is covered with unsolidified liquid polymer,….*", actually giving the description of the main core procedure of the stereolithography technology. Kodama's experiments, and papers, are nowadays considered to be the first successful application of working additive manufacturing (AM) techniques worldwide.

The real market-available additive manufacturing, however, first saw light in 1987 with stereolithography (SL) from 3D Systems. Their process involved solidification of thin layers of light-sensitive liquid resin polymer using a UV-laser beam. They marketed their SLA-1, being the first commercially available AM machine worldwide. This system was the precursor of the SLA 250 machine, which became a commercial success (SLA acronym means Stereo-Lithography-Apparatus). SLA 250 was replaced by Viper SLA, and nowadays replaced by the ProJet series of SLA Printers.

A year later, in 1988, 3D Systems and Ciba-Geigy formed a partnership aiming at the development of stereolithography materials and marketed their first-generation acrylate resins. DuPont developed its stereolithography system named Somos along with proper resins in the same year. Loctite had also attempted to enter the SL resins market in the late 1980s, but closed the corresponding department in 1993.

Japan's NTT Data CMET and Sony/D-MEC commercialized versions of stereolithography in 1988 and 1989, as an answer to 3D Systems SL in the U.S. NTT Data CMET (now a part of Teijin Seiki, a subsidiary of Nabtesco) called its machine Solid Object Ultraviolet Plotter (SOUP) and Sony/D-MEC (now D-MEC) called its device Solid Creation System (SCS). Sony closed its production for SL systems for D-MEC in 2007. In 1988, Asahi Denka Kogyo introduced the first epoxy resin for the CMET SL machine. In 1989, Japan Synthetic Rubber (now JSR Corp.) and DSM Desotech started to supply polymers for the Sony/D-MEC stereolithography machines.

In 1990, Electro Optical Systems (EOS) based in Germany sold its first Stereos stereolithography system. The same year, Quadrax introduced the Mark 1000 SL system, which employed visible light resin. The following year, Imperial Chemical Industries introduced a visible light resin product for the Mark 1000. ICI stopped selling its resin about 1 year later when Quadrax dissolved due legal issues with 3D Systems.

1.2. Layering systems-non SL

Back in 1991, three AM technologies were made available to the market, e.g., fused deposition modeling (FDM) as coined by Stratasys, solid ground curing (SGC) marketed by Cubital, and as mentioned above, laminated object manufacturing (LOM) by Helisys. FDM utilizes molten thermoplastic polymers in the form of a filament to structure an object in a layer-by-layer fashion. In SGC, a UV-sensitive liquid polymer is used, and each complete layer solidifies in each laser scan by ample UV light which passes through masks created using an electrostatic toner on a glass plate. LOM cut sheet material using a digitally guided laser and bonds the stacked layers together into a 3D object. Cubital and Helisys are not in the market anymore. Selective laser sintering (SLS) from DTM (now a part of 3D Systems) and the Soliform stereolithography system from Teijin Seiki became available in 1992. Using laser as an extreme heat source, SLS sinters powder materials by local fusion. DuPont had developed the Soliform technology originally, under the name Somos and licensed it to Teijin Seiki. The latter company had the exclusive distribution rights in parts of East Asia. Also, in the same year, a company called Allied Signal marketed vinylether Exactomer resin polymers for SL applications. In the next year, Soligen of Germany presented a device under the name direct shell production casting (DSPC). DSPC employed an inkjet printer mechanism, which deposited liquid binder onto ceramic powder. In this way, shells were formed for later use in the investment-casting procedure. The patent Soligen used was filed by the Massachusetts Institute of Technology (MIT). In January 2006, Solingen stopped its production of DSPC systems. That year, Denken marketed an SL system that featured a solid-state laser. It should be mentioned here that Denken's SL system was presumably, compact enough, to sit on a bench top. Moreover, it was also given away at a relatively low price, compared to other SL systems available in the market. In 1993, 3D Systems and Ciba made their first epoxy resin product for SLA, commercially available. In the same period, the QuickCast structuring scheme was presented. QuickCast, still used to-date, is a process in which hollow investment-casting molds are produced. After casting, the polymer mold would burn out, without damaging the fragile ceramic shell. In 1994, many new additive manufacturing systems found their way into the markets. ModelMaker from Solidscape (then called Sanders Prototype) was delivered, as many new systems from Japanese and European firms did. By making use of an inkjet print head, ModelMaker had the ability to deposit waxy materials layer, by layer. Aiming at a new market sector, namely jewelry makers, Meiko in Japan produced a novel small stereolithography device. Meiko is no more in the SL sector since 2006. Also, in Japan, KiraCorp. marketed its first non-stereolithographic device. The device called Solid Center was actually a complete LOM system featuring a typical laserprinter engine, toner, an x-y plotter, and knife; it was able to produce wood-like models by paper lamination. Kira referred to Solid Center as the first plain-paper 3D printer. In the same year 1994, Fockele & Schwarze (F&S) in Germany introduced a stereolithography machine, but on a limited basis, and a German company named EOS commercialized a printer called EOSINT based on laser-sintering technology. Ushio from Japan (Unirapid Inc. nowadays) sold its first stereolithography machine in 1995.

1.3. Low-cost 3D printers

In 1996, Stratasys introduced the Genisys machine. This type of printer utilized an extrusion process similar to FDM, however, based on technology developed at IBM's Watson Research Center. Being a decade almost in the market of stereolithography systems, 3D Systems offered to the market its first 3D printer (Actua 2100) in 1996, using a technology that deposits waxy materials in a layer after layer fashion, utilizing an inkjet-printing mechanism. In the same year, a company called Z Corp. marketed its Z402 modeling 3D printer, aiming at conceptual use. The Z402 machine profited from MIT's inkjet-printing (3DP) technology, and models were manufactured using starch- or plaster-based powders and a water-soluble liquid binder. Also in 1996, Schroff Development started to offer to the market its semi-automated paper lamination system below the threshold of $10,000. BPM Technology begun to sell its Personal Modeler 2100 model in 1996 too. By employing a process named ballistic particle manufacturing (BPM), the machine could deposit waxy material layers by use of an inkjet-printing head. The company ceased operations in October 1997. Kinergy based in Singapore started selling its Zippy paper lamination systems, which worked much alike as the LOM process. AeroMet founded in 1997 was a subsidiary of MTS Systems Corp. This company developed a procedure called laser additive manufacturing (LAM) that employed a high-power laser and titanium alloys in the form of powder. Until it stopped operations in December 2005, AeroMet was a 3D printed parts subcontractor for the aerospace industry. That year, Ciba acquired the Exactomer resins business from Allied Signal. In 1998, Yinhua Laser Rapid Prototypes Making & Mould Technology Co., Ltd. based in Beijing-China, intensively pursued the marketing of its products. Not by chance, Tsinghua University in Beijing, being the original developer of these systems, has developed processes much alike to FDM and other additive manufacturing technologies, since 1996. Autostrade started to market a stereolithography system called E-DARTS to firms in Japan at prices no higher than $25,000, in the same year. Also in 1998, Optomec made available to the industry its laser-engineered net shaping (LENS) metal powder system. The machine was based on the technology developed at Sandia National Labs. From that point, the markets begin to open even more and also the international demand for such systems. In March 1999, 3D Systems introduced a machine called ThermoJet, a much faster and less costly version of Actua 2100. At that time, 3D Systems was selling its SLA 7000 system for $800,000, which was the most expensive AM system for plastic materials, available worldwide. In April 1999, on demand by Motorola, a company under the name Extrude Hone AM business (nowadays named Ex One) installed its first ProMetal RTS-300 system, for building metal parts. The machine was utilizing MIT's 3DP inkjet-printing technology. In 1999, Fockele & Schwarze based in Germany, revealed its selective laser-melting system for steel-based powders. This system was developed in cooperation with the Fraunhofer Institute for Laser Technology, in Aachen. The same Institute provided know-how for Röders, who developed and sold its controlled metal buildup (CMB) machine. Also, in 1999, DSM acquired the Somos branch from DuPont. In January 2000, Helisys announced that Toyoda Machine Works of Japan would manufacture and sell LOM systems in Japan. In June 2000, Toyoda exhibited its proprietary machine based on LOM technology, at a technology fair in Tokyo. Sanders Design International proclaimed the development of a system named Rapid Tool Maker (RTM) in January 2000, and they also announced that it had licensed the RTM technology to a German company called Buss Modeling Technology (BMT). BMT, which was formerly Buss Müller Technology, had the strategic plan to manufacture RTM systems and provide it to the European markets. At that time, BMT announced manufacturing and marketing a color 3D printer based on powder and binder technology, developed by Aad van der Geest of the Netherlands. The process was quite similar to the 3DP process from Z Corp.

Since the beginning of the first decade of the new century, many systems are available in the market for producing layered structures, now under the name 3D printed structures utilizing the prevailing technologies as described above in summary and in the following chapters in detail. Nowadays, many affordable systems are available in the open market, even as DIY kits, for applications in almost all industrial sectors as well as for hobby and recreation as it will be shown.

2. Market placement

Up to year 2009, layering technology of 3D printing was largely employed for industrial applications, as reported above; however, exactly then, the patent protecting fused deposition modeling (FDM)—one of the most simple and commonly used 3D printing technologies nowadays—expired. Thanks to the RepRap people's project's mission and vision, to build a self-replicating 3D printer, the first desktop 3D printer was born. This caused an avalanche effect and many manufacturers followed, and the cost which was initially $200,000 back in early 2000, suddenly sunk below $2000, and the consumer 3D printing market took off in 2009. Nowadays, a simple DIY system costs about $150 for hobbyists.

The sales and market of 3D printing have been skyrocketing ever since. Of course, important patents on additive manufacturing expired and technology is made available to more bright minds, hence more innovations are foreseen in the near future as well as enormous revenues in the main and niece markets. There are, nowadays, almost 300,000 enterprise users and more than 1,000,000 private owners of 3D printers in the world. These numbers are doubling every other year. 3D printing industry is still in its childhood phase and its growing bigger and bigger. The number of companies that manufacture 3D printers has doubled in the last 2 years. According to Wohler's Report for 2017, 97 manufacturers produced and sold additive manufacturing machines and devices in 2016. A year later, they were 62. The industry achieved worldwide revenues of $6.063 billion in 2016 about three times the maximum forecasted value as seen in **Figure 1**.

2.1. 3D printing: advantages and disadvantages

It is of paramount significance to understand that 3D printing is a rapidly developing technology, rather immature, which comes with its family of inherent benefits, but also lags behind traditional manufacturing processes in many aspects. Examples from all aspects will enable the reader, get a grasp of these factors and foresee where the technology is headed in the near future.

3D printing allows designers and engineers create complex shapes and parts—many of which cannot be produced by traditional manufacturing techniques. Of course, evidently, manufacturing through additive methods implies that complexity comes at a price; elaborate product designs with complicated design features now cost just as much to produce as simple product designs that follow all the traditional rules of conventional manufacturing.

Utilizing traditional production methods, at a high volume or numbers of products, it is simply cheaper to make and sell products at reasonable prices to the consumer. Alternatively, 3D printing allows easy customization; one only needs to change the design digitally in CAD software to make changes with no additional tooling or other expensive or high efficiency

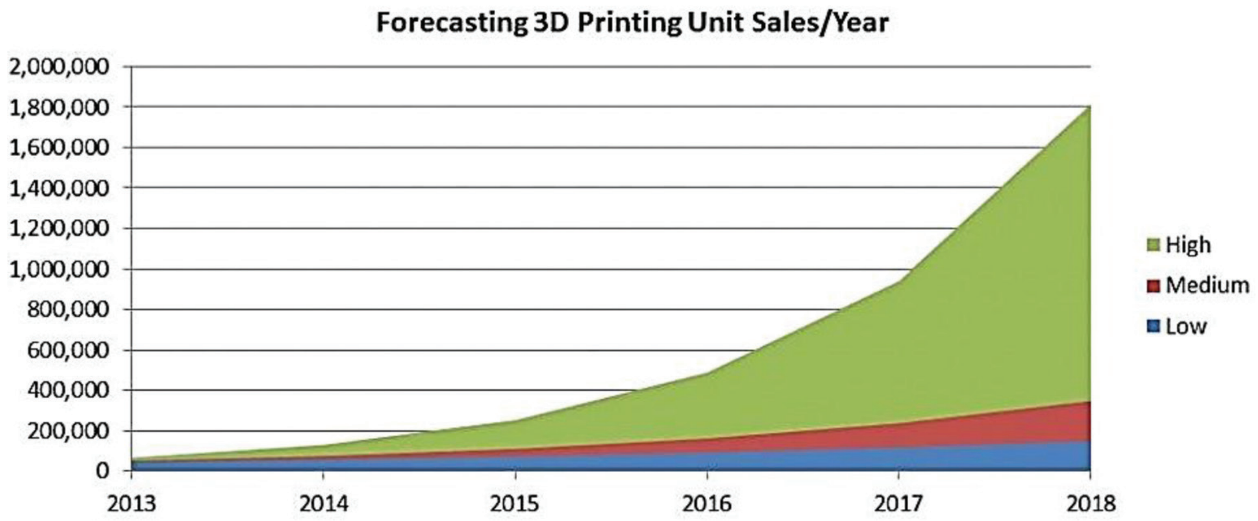

Figure 1. Estimated 3D printer sales per year from 2013 to 2018 [4].

manufacturing processes required to produce the final product. This results in an item that can be customized to meet a user's specific needs without additional manufacturing costs, only the design labor remaining.

In metal casting or injection molding, each specific part of each product requires a mold—a factor that can skyrocket manufacturing costs rapidly. To counteract these permanent manufacturing costs, most companies anticipate thousands of the same items being sold. On the other hand, 3D printing is *per se*, a "single tool" or maybe a zero-tool process. In this way, no tool is required and no need to change any condition of the process exists. Additionally, no hidden costs or lead times are involved in making an object complex or simple. Consequently, this paves the way for substantial decreases in production costs. At the cost of manufacturing time of course, needless to mention, as situation stands nowadays, because 3D printing is by no means considered a mass production technology.

Strategically thinking, once its manifested that there is no expensive tooling required to produce objects through 3D printing technologies, designers or entrepreneurs, might consider it, and they usually do so, as a cost effective method to produce items for a market test run or small production series. Possibly best, exploit the internet, through crowdfunding sites like Kickstarter, in order to launch their products. At the early stages of product development, it appears both also practical and wise to make design changes, in the product, without compromising their name in more formal—and expensive—manufacturing orders. Concluding, 3D printing technology opens a much less dire route to the market for those who want to materialize a novel product or an idea.

Most conventional manufacturing processes are subtractive especially the second grade ones: you start with a block of material (or a cast item), and usually through cutting, milling, drilling or similar, it is being processed at the intended final design. For many products—such as a bracket for an airplane—90% of the raw material is lost during processing.

On the other hand, 3D printing belongs to the additive processes; object is created from the raw material layer-by-layer. According to the laws of Mother Nature (she creates things exactly this way we found), when an object is manufactured this way, it only uses as much material—and energy—that is needed to create that particular object and no more. Additionally, most of these materials can be recycled and repurposed into more 3D-printed objects.

Alas, having all of the benefits of manufacturing through additive techniques, 3D printing is not yet competitive with conventional manufacturing processes, when it comes to large production volumes. The critical turning point lies between 1000 and 10,000 units, the numbers being a function on the material and the design. Of course, as the prices of printers and raw materials continue to decrease, the range of efficient production is expected to increase above the reported numbers in the following years.

Nowadays, there are more than 600 3D printing raw materials marketed, most of which are plastics and metals, but the choices are still limited compared to conventional product materials, available colors and finishes. The pseudo-lack of materials, however, is increasing, the number of new materials added to the 3D printing palette is growing rapidly now including wood, metals, alloys, composites, ceramics, and even chocolates.

A key aspect, of course, is the mechanical properties. In most 3D printing technologies, the part strength is neither uniform nor high, due to the layer-by-layer fabrication process. Practically, parts that have been 3D printed are usually weaker than their traditionally manufactured counterparts. Repeatability is also an open question; parts made on different 3D printers might have varying properties. However, as technical improvements are rapidly achieved and as novel continuous 3D printing processes like Carbon3D are made available, these disadvantages are prone to extinct in coming years.

Despite, the fact that we are not still able to manufacture 3D-printed objects with submicron tolerances like an iPhone, 3D printing technology is considered as a very straightforward and practical procedure of layering objects. These parts feature precision within the scale 20–100 microns, which correspond to a natural scale from the diameter of a human hair to the height of a single sheet of paper. 3D printing enables designers and engineers, who are creating objects with few tolerances and design details, to make products and bright ideas real. As known, many high-tech objects demand fine working parts and even finer details—such as the silent switch on the iPhone—it is still difficult to compete with the high precision capabilities of certain manufacturing processes, but time will prove this technology in every case. In every case, 3D printing is changing business model innovation in a very rapid manner (**Figure 2**) [7].

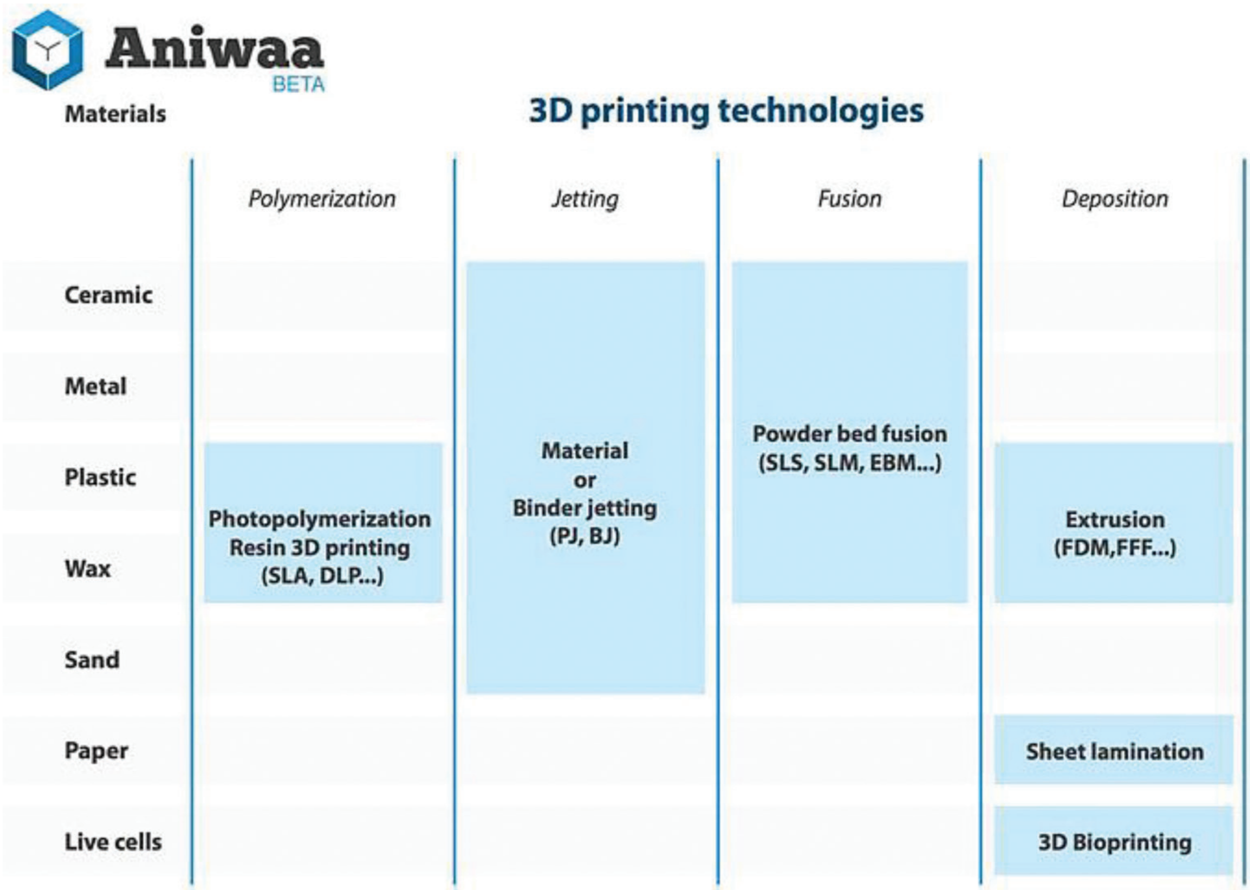

Figure 2. Available technologies and materials for 3D printing and lamination techniques. Source: www.aniwaa.com.

3. 3D technologies review

This part refers to the main 3D printing technologies which enable us in printing layered structures in some detail. Only the principal ones in use nowadays are reported, and some innovative ones are shown in the applications chapter.

3.1. Fused deposition modeling (FDM)

The FDM printing process begins with a string of solid material called the filament. This line of filament is pulled from a reel attached to the 3D printer to a heated nozzle inside of the 3D printer that heats the material above its melting point. Once in a melted state, the material pushed out of a nozzle is extruded on a specific and predetermined path guided by the software on the computer usually instructed in G-code language. As the material is extruded, as a layer of the object on this path, it instantly cools down and solidifies—providing the base for the next layer of material until the entire object is manufactured.

Considered nowadays as the cheapest 3D printing technology commercially available, FDM also offers a wide variety of plastic-matrix materials in a rainbow of colors including ABS, PLA, nylon, and blends with more exotic materials, including carbon, bronze, or wood (**Figure 3**).

FDM is a considered to be the most practical choice for quick and low-cost prototyping. It can be used for a wide range of applications and objects with a typically wide palette of polymers as filaments in pure or reinforced form. Recently, FDM 3D printing has become very famous among hobbyists for enabling them to design and produce functional products, with embedded electronics and mechanical parts such as drones. FDM 3D printing is hampered by

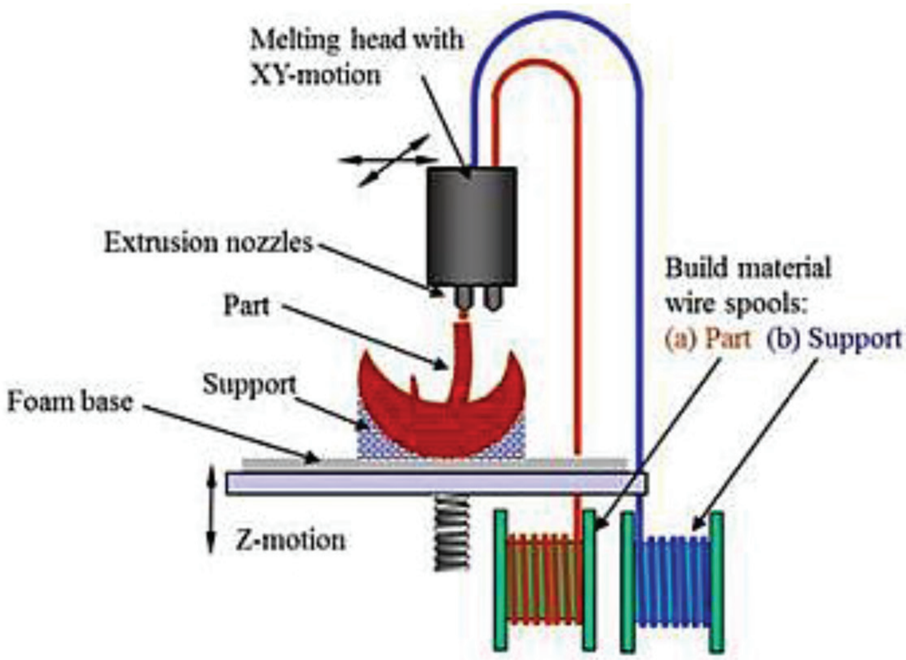

Figure 3. FDM technique sketch. Source: Caliskan and Durgun [5, 6].

design and material limitations, although improvements appear almost continuously nowadays. The technology generally is not considered suitable for more intricate designs or where high strength is required [8]. Usually, the parts manufactured with this technique can exhibit some internal anisotropy due to layering procedure [9].

3.2. Stereolithography and digital light processing (SLA & DLP)

These techniques are reported together, due to the fact that both technologies produce 3D-printed parts using a photo polymerizing polymer resin, featuring a UV light source to cross-link the liquid material [10].

Analytically, the procedure is as follows: a building platform submerges into a translucent tank (vat) filled with the liquid photo polymerizing resin. After submerging the tank, the UV light source located inside the machine, focuses through the bottom of the tank, scans each layer of the object, effectively solidifies-crosslinks, or polymerizes the material in other words. Consequently, the platform is lifted upward by a few microns, thus allowing a fresh layer of resin to flow beneath the object. The UV light source shall map and solidify the new layer onto the previous one. Micron-by-micron step, the process is repeated in a layer-by-layer fashion, top to bottom until the whole part is finished. The methods are differentiating only by the light source used: In SLA, a UV-laser is used; whereas in DLP, a UV-projector lamp is employed.

The progress made in the past decades delivered enabled 3D printing processes to be applied in desktop 3D printers. Needless to mention here, materials selection is limited to UV-crosslinked polymers. The materials selection, however, broadens each year, new resins with enhanced strength or flexibility are available on the market.

One of the most favorable advantages of SLA & DLP 3D printers is the high accuracy in the produced objects characterized by very smooth surface finishes. This makes them especially famous among artists, for manufacturing sculptures, jewelry molds, and other prototypes. On the other hand, the SLA-DLP technologies are not suitable for printing relatively large or high strength objects. The technology has been accessed as a useful tool in biomedical engineering too [11] (**Figure 4**).

3.3. Selective laser sintering (SLS)

In the process called selective laser sintering (SLS), a high-power laser is required. The laser is employed in order to melt and solidify layers of powder and produce, again layer-by-layer, 3D objects. The SLS printers are commonly equipped with two plates called pistons. First, a first layer of powder is laid onto the fabrication piston. The high-power laser maps/scans the first layer in the powder, thus selectively melting and sintering—the powder material [12]. In this way, the first layer is fabricated. After solidification of the first layer, the fabrication piston is slightly lowered, and the powder delivery bed, in which the power is contained, is raised by some microns. Then, a roller forces another layer of powder on top of the previous solidified layer. The aforementioned procedure is repeated, allowing the laser to melt and solidify all successive layers one by one, until the designed part has been finished bottom to top (**Figure 5**).

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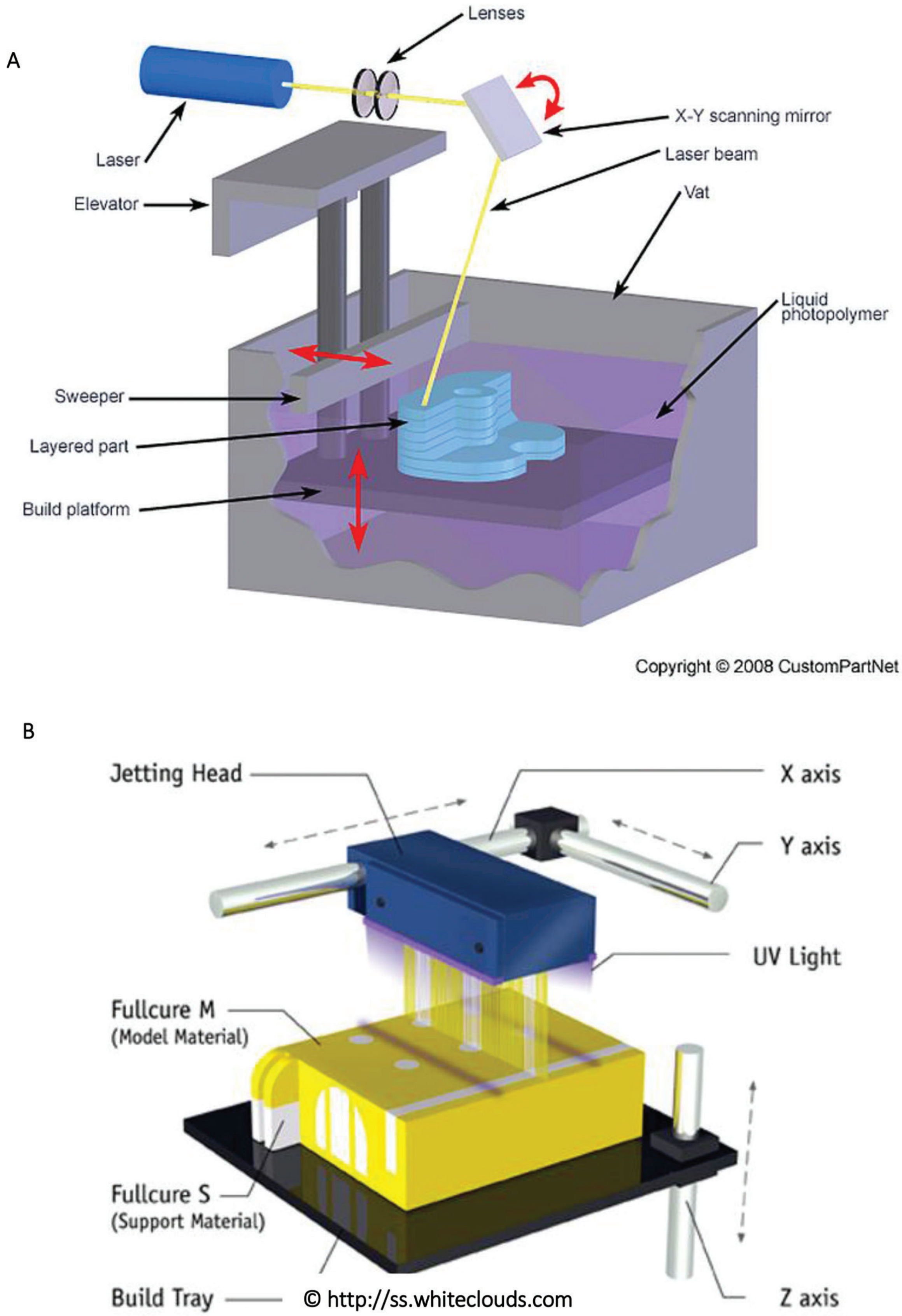

Figure 4. (A) Stereolithography (SLA) vs. (B) digital light processing (DLP) techniques.

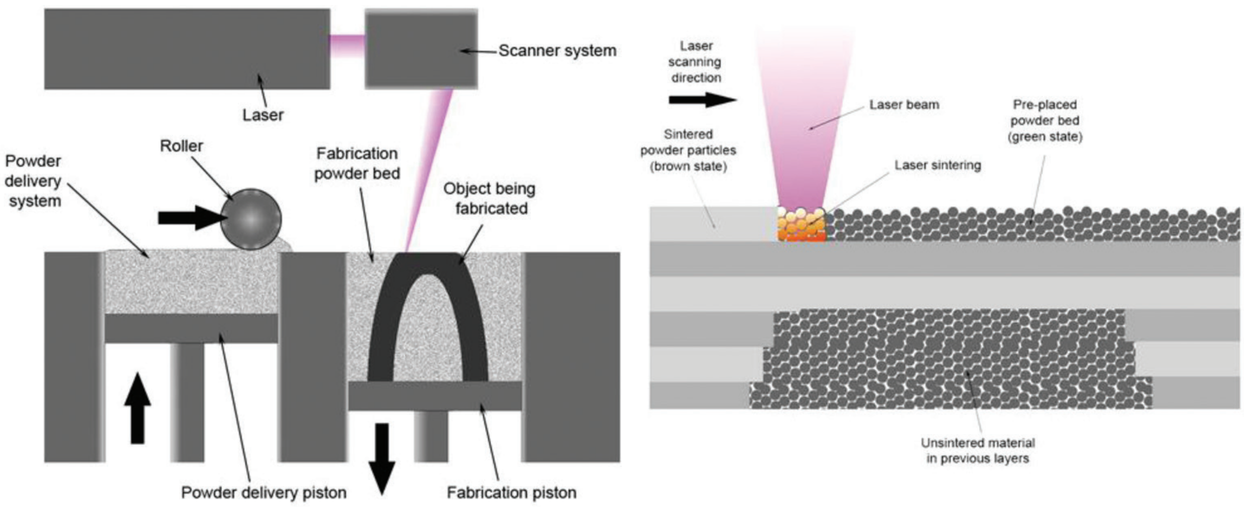

Figure 5. Selective laser sintering (SLS) method. © Materialgeeza—own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=4032088.

SLS is a highly efficient method, though rather expensive, but has established itself into the industrial 3D printing applications. Desktop SLS printers are widely available on the open market, and prices are already quite affordable. In 2017, a small SLS system could be acquired for as much as $15,000. The usual materials available nowadays as powders for SLS include most thermoplastics such as polyamides (nylon), polystyrene, thermoplastic elastomers, etc.

Due to its high accuracy and production fidelity, SLS machines are widely used for manufacturing end products as well as functional prototypes. Complete design freedom is its most important advantage. There is no need for support of structure. The surrounding unmolten powder acts as a support for the structure as it is layered, which allows for complex, sophisticated, and delicate shapes to be manufactured. Finished objects, as a side effect, take a bit more time to cool, and thus longer lead times are expected. Excess and attached object powder is removed by blowing air or using high pressure water or liquids, and is recycled after filtering; hence, economy of raw materials is *in situ* achieved.

3.4. Metal printing (selective laser melting and electron beam melting)

Selective laser melting and electron beam melting (SLM and EBM) are two of the most common metal 3D printing technologies. They are considered as offspring of the SLS technique described above. Just like SLS, these processes create objects from thin layers material. Raw material is the form of powder and it is selectively melted using an intense heat source. As metals and also ceramics, are characterized by higher melting points, consequently much more power is required; this is provided by a high-power laser for SLM or even an electron beam in the EBM technology.

The printing process begins by distribution of a thin layer of metal powder onto a build plate. The powder is selectively melted by a laser (SLM) [13] or an electron beam (EBM) [14] which maps the object layer. The platform or build plate is afterwards lowered by some microns and

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rapidly coated with new layer of metal powder on top of the solidified layer. The process is repeated until all layers have been solidified resulting in the finished part. Contrary to SLS, the SLM and EBM techniques require support structures, in order to stabilize the object to the build platform and enable manufacturing of overhanging parts. As a side effect, these enable heat transfer away from the solidified powder. Moreover, SLM is performed in a low-oxygen environment and EBM in vacuum. These conditions enable thermal stresses reduction and warping prevention, and they also allow reactive metals and alloys to be used as raw material.

Due to their high accuracy and costs, SLM and EBM are mainly applied in industrial 3D printing. Materials include various metals and alloys including steel, titanium, aluminum, cobalt-chrome, and nickel.

Metal printing is considered to be as the “holy grail” of additive manufacturing and 3D printing; it has found its path in the aerospace, aircraft, automotive, and healthcare industries for a range of high-tech, low-volume part production, from prototyping to final production. 3D printed metal parts allow for monolithic structuring (reducing the quantity of components), miniaturization, and mass reduction combined with design optimization, as shown in **Figure 6**. SLM and EBM have evolved to a stage where these prints are directly comparable to traditionally manufactured parts in terms of chemical composition, mechanical properties (static and fatigue), as well as microstructure. In the year 2017, for the first time, direct metal laser sintering (DMLS) devices, as the latest generation of SLM printers are referred to, were presented in the market at a cost lower than $100,000. Prices for such systems in the previous years were over half and near 1 M$.

Figure 6. A stainless-steel bracket optimized for weight reduction (front) and the traditional cast bracket in the back. Source: European Space Agency events via Flickr.

4. Advanced applications of the technology of 3D manufacturing

4.1. Automotive industry

3D printing is becoming more and more a familiar technology to the automotive industry, enabling manufacturing of not only prototypes but also finished parts as well. In February 2017, BMW iVentures, the automaker's venture capital arm, announced an investment in Desktop Metal, a startup devoted to 3D printing metal objects. BMW wants to help accelerate the rollout of this technology in both its design and manufacturing departments. In Formula 1, quite a few racing teams have been testing and ultimately creating custom car parts, using 3D printing for prototyping that are used in high speed races. In the same spirit, Swedish car manufacturer Koenigsegg employed 3D printing to manufacture the variable turbocharger for their One:1 model—a car that has an astonishing 1:1 HP-to-Kg curb weight ratio. Although the 100% metal part is not only very lightweight, more importantly, it can also endure the high forces of supercar combustion and demanding racetrack conditions. Other high-tech examples include Ai Design company's bespoke interior items for high-end cars with popular items including housings for radar detectors, iPhones, and aftermarket SatNav units that blend in with the car's interior. The company often services customers with Lamborghinis, Ferraris, and classic Bentleys, so the fit and finish on the OEM-grade thermoplastics has to be perfect. Ai's experienced engineering was reluctant to abandon the highly efficient CNC manufacturing behind. It took a lot of expert consulting from Stratasys to make Ai Design's people to comprehend the potential in manufacturing its models with a 3D printer and fused deposition modeling.

BMW, as mentioned above, went for 3D printing technologies quite early. The company has its own Rapid Manufacturing Facility at the HQ in Munich. BMW is considered to be of the founding fathers of stereolithography having recently revealed plans and approach for a fully 3D printed car. One can understand how deeply 3D printing has become incorporated into the company culture by the fact that even a thumb cast for assembly line workers was produced in that way. Evidently, the workers have to push by thumb, a huge number of rubber plugs into chassis holes on the assembly line. This repetitive work causes a repetitive strain type injury in many of them. Confronting the issue, BMW engineers came up with a bright idea: a cast of the thumb and hand that relieved all the strain out the process. Quite simple, very brilliant, and it just proves just how deep 3D Printing has gone into the corporate culture at BMW. It also shows that 3D printing goes beyond the actual manufacturing process itself into biomechanics and ergonomic concepts (**Figure 7**) [15, 16].

4.2. Medical and dental industry

Being always at the cutting edge of technology, biomedical and prosthetics fields has largely benefited from the introduction of 3D printing in these sectors. Custom-shaped personalized-hearing aids no longer require manual labor to manufacture; with 3D printing, they can be made with the click of a button in a very short time. This of course implies substantially lower costs and shorter production times. Even orthopedic implants manufacturing at custom dimensions from CT or MRI scans from the patients is nowadays feasible.

Figure 7. BMW has turned to 3D printing to augment its workers and stop strain on limbs frequently found on manufacturing lines. Photograph: BMW (republished from the Guardian).

Prosthetics and other assistive medical devices, braces, and retainers are tailored specifically for the needs of the patient. This has totally reversed an inherent problem that of time and energy required to manually produce each product. As a natural consequence, introduction of 3D printing in the dental and orthodontics fields was an inevitable event. With today's technology, a dental surgeon or orthodontist can use an intraoral 3D camera to scan a client's oral cavity and teeth, use afterward a specialized software and digitally design dental prosthetics, braces, crowns, bridges, etc. Then, he can send the files to a dental technician to 3D print the required molds or directly print the prosthetic itself. As if it was meant to be invented for them the dental industry fully adopted 3D printing technologies. Nowadays, there are dedicated 3D printer models produced specifically for manufacturing dental aids and molds. Alone 3D printer company Stratasys offers two wax 3D printers available to the dental industry. The Stratasys CrownWorx and FrameWorx 3D Printers are supposed to provide the highest precision in wax 3D printing, allowing dental laboratories to produce wax-ups for crowns, bridges, and denture frameworks. Imagine economy in time and costly silicon imprinting materials and gypsum molding. 3D Printers for dental applications such as Stratasys CrownWorx and FrameWorx use wax deposition modeling (WDM) technology. Mainly based on jetting technology and waxy polymers, they allow production of wax-ups characterized by smooth surface finishes and minimal post-processing effort and time requirements. Stratasys claims that the waxy materials burn out leaving no residue, no material shrinkage, neither invoking cracking, nor expansion (**Figure 8**).

Nowadays, many types of 3D printers are used also in other areas of biomedical applications, such as manufacturing scaffolds for tissue engineering [17, 18] and many other areas of biomaterials engineering [19].

4.3. Aerospace

SpaceX designed and built its famous SuperDraco hypergolic propellant liquid rocket engine. It is a member of SpaceX's Draco rocket engines family. Dragon V2 passenger-carrying space

Figure 8. An example of a dental frame built using wax deposition modeling. Source: www.Stratasys.com.

capsule shall be powered by a redundant array of eight SuperDraco engines. These provide fault-tolerant propulsion in the launch escape system and propulsive-landing thrust (**Figure 9**).

The combustion chamber of the SuperDraco space engine is created with direct metal laser sintering (DMLS), using Inconel powder. This super-strong nickel-chromium-based "superalloy" is quite difficult to machine in the traditional way with CNC's. The use of 3D printing DMLS technology "*resulted in an order of magnitude reduction in lead-time compared with traditional machining – the path from the initial concept to the first hotfire was just over three months*," according to the company's website. Moreover, the combustion chamber is regeneratively cooled. This method allows cryogenic propellant to pass through a jacket covering the combustion chamber, cooling thus the engine, a trusted solution in the rocker motor design technology.

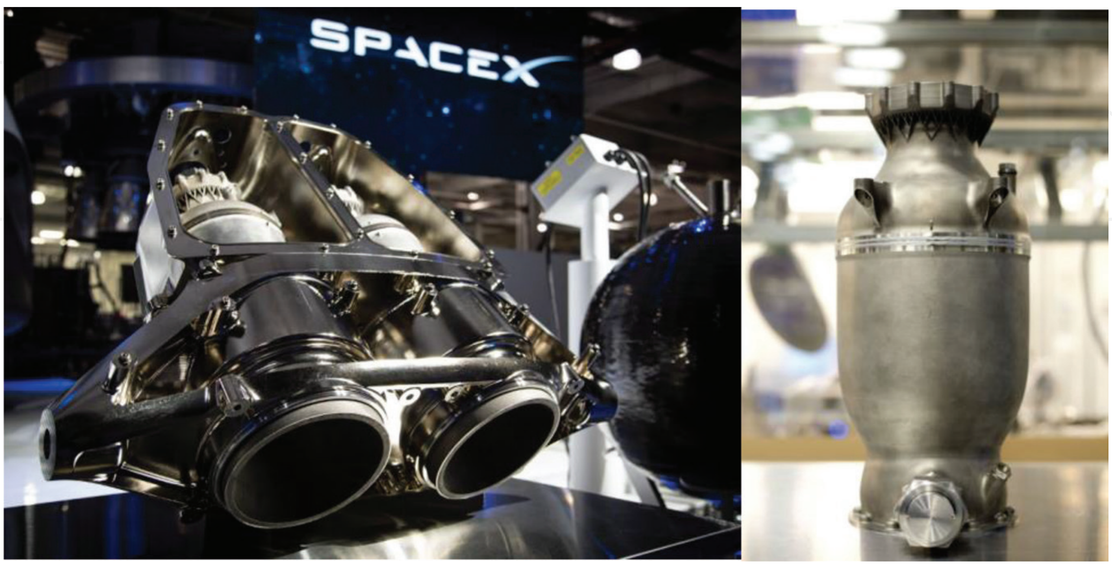

Figure 9. SPACEX, Superdraco engine [20].

On the other hand, in early 2016, rocket and missile propulsion manufacturer Aerojet Rocketdyne, a renowned aerospace and defense leader, was the recipient of a $6 million contract from the US Air Force to define 3D-printed rocket engine component standards. The standards will be used to qualify the 3D printed components used in liquid-fueled rocket engine applications, in order to follow through with a mandate set down by US Congress: that the Department of Defense will stop using Russian-made RD-180 engines to launch US satellites and national security payloads into space and begin using domestically produced options instead. Shortly after, Aerojet signed its own contract with Sigma Labs, to non-exclusively license its PrintRite 3D software system to evaluate and redefine the 3D-printed components used in Air Force manufacturing (**Figure 10**).

Aerojet, being certainly the right company for the Air Force contract, had already successfully completed hot-fire testing of the 3D printed rocket engine injectors for its liquid-fueled AR1 booster rocket engine in 2015; selective laser melting was used to manufacture the components. It has been known that Aerojet has also successfully completed its Critical Design Review (CDR) for the 500,000 foot-pound thrust-class AR1 engine. This achievement will keep the AR1 on track for flight certification in 2019, as a replacement for the Russian RD-180 engine. Twenty-two incremental CDRs came before the recent system-level CDR, along with full-scale testing of critical subsystem components, like the staged combustion system.

In the aviation sector, GE Aviation and Safran companies have successfully launched a method for 3D printing of jet engine fuel nozzles. The remarkable technology allows engineers to replace complex assemblies with a single part. The 3D-printed nozzles are lighter than previous designs, and boost a jet engine's fuel efficiency by up to 15%. LEAP engines of GE equipped with 3D-printed fuel nozzles which will power new generation narrow-body planes, e.g., Boeing 737MAX and Airbus A320neo. Especially, the A320neo Airbus passenger airplane is powered by twin LEAP jet engines with 3D-printed parts based on new advanced materials. LEAP ("Leading Edge Aviation Propulsion") is a high-bypass turbofan engine which, due to its advanced space age materials operates at higher pressures than the previous CFM56 machine. The LEAP is the first engine equipped with actually 19 (!) 3D-printed fuel nozzles and parts

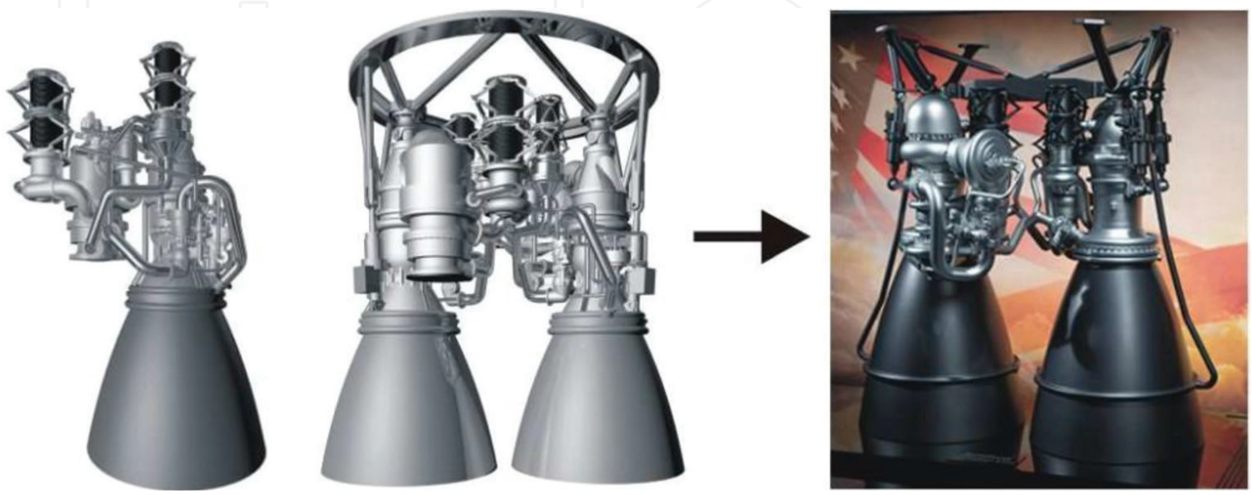

Figure 10. The Aerojet Rocketdyne AR1 booster engine can be configured as a single engine or a twin booster.

from space age, super-strong ceramics that make it 15% more fuel efficient than the previous CFM56 airplane jet engines built by CFM International. CFM is the 50/50 joint-venture between GE Aviation and France's Safran (Snecma) who designed the engine. Airbus picked the LEAP for the A320neo in 2010. Since then, CFM has received more than 2500 orders and commitments for the LEAP-1A engine, representing 55% of A320neo orders to-date (**Figures 11** and **12**).

In August 2016, the LEAP engine was installed on the Airbus A320neo with Pegasus Airlines and CFM delivered 77 machines. Following the introduction of Boeing 737 MAX, CFM delivered 257 LEAPS in the first 9 months of 2017, including 110 in the last three: 49 to Airbus and 61 to Boeing, and targets 450 in the year. The predictions for production at CFM are 1200 engines in 2018, 1900 in 2019, and 2100 in 2020, respectively. This is compared to the 1700 CFM56 produced in 2016. FAA has recently certified the first 3D-printed part for a GE jet engine—a casing that houses the compressor inlet temperature sensor inside the GE90 jet engine.

Figure 11. An Airbus A320neo powered by a pair of LEAP-1A engines took a maiden flight on May 19 in Toulouse, France. The two engines used for the four-and-a-half-hour flight were the LEAP-1A, developed specifically for the Airbus jet [21].

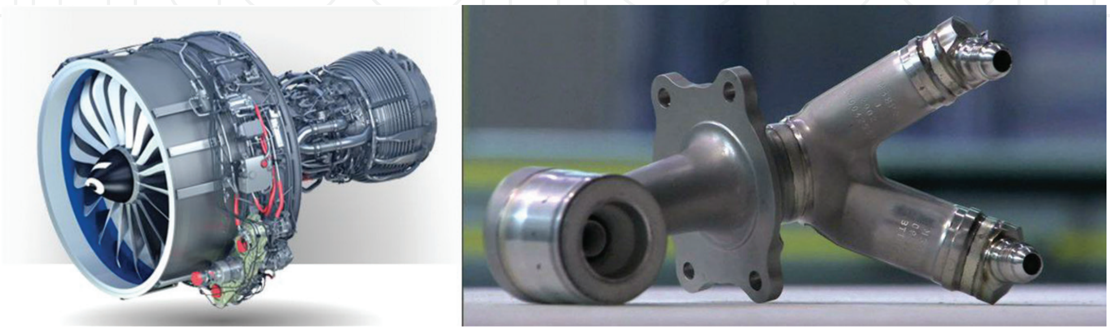

Figure 12. The LEAP engine (to left) has 19 3D-printed fuel nozzles (top right) and static turbine shrouds made from ceramic matrix composites (CMCs) (above left). Image credit: CFM.

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4.4. Fuel tanks

In the totally innovative additive manufacturing process technology invented by Sciaky [22, 23], it is possible to build the two hemispherical halves of fuel tanks. Layer-by-layer, spools of titanium wire is spun, providing the material which melts and deposits, forming thus the tank walls. Lockheed Martin Space Systems, after carefully reviewing and applying the process, stated that they plan to re-think the way they produce satellite propellant tanks. Moreover, eventually the construction of those tanks will be shifted in-house, and thus results in significant capital savings. Up to this point, Lockheed Martin bought those critical titanium tanks from Orbital ATK. The three Mars orbiters use the Orbital ATK tanks as will NASA's OSIRIS-Rex asteroid-probing space vehicle upon its completion and launch. Lockheed Martin official Ambrose stated that it has become critical to reduce the lead times for building satellites, and he said that 3D printing holds the keys to reaching that goal (**Figure 13**).

Sciaky Inc. had already begun developing the wire-feed electron beam process back in the mid-1960s [24]. The process was further developed in the 1990s allowing for production of jet engine knife edge seals [25]. The EBAM process was more advanced early in the 2000s, allowing manufacturers' significant savings in time and money on the production of large, high-value metal parts. Sciaky formally launched the EBAM process, in 2009, which was then marketed as Electron Beam Direct Manufacturing, as a service option. Lockheed Martin Aeronautics selected Sciaky for the Department of Defense (DOD) Mentor-Protégé Program in 2011. The special focus of this agreement was the application of additive manufacturing for titanium structural components for Lockheed Martin's F-35 Lightning II fighter project. Further on, in 2012, Sciaky signed a partnership with Penn State University, via DARPA (Defense Advanced Research Projects Agency) funding. Their goal was to advance Direct Digital Manufacturing (DDM) technologies for highly engineered and critical metallic systems and components in applications for the Department of Defense (DOD) and US industry.

Finally, in 2014, Sciaky started delivering fully operational commercially available EBAM systems. Needless to mention, Lockheed Martin Space Systems was one of the first customers to acquire an EBAM system for developing and producing "3D-printed" titanium propellant tanks. The EBAM system which Lockheed bought last year from Sciaky Inc. costs $4 million and is capable of "printing" out fuel tanks of nearly 150 cm in diameter. There is even better news: the method cuts down the cost of manufacturing propellant tanks by as much as 50%.

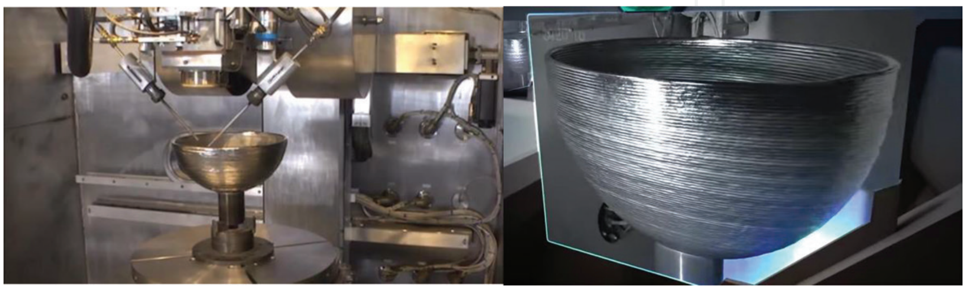

Figure 13. The manufacturing procedure of one half of a satellite fuel tank according to the Sciaky method (top left) and finished half-product (top right). Source: Sciaky Inc. Video capture.

The process is also much faster than casting those tanks in molds. With around 20 months being the lead time of the casting technique, and the time spent procuring the bulk, forged titanium billets also considered, EBAM additive manufacturing is considerably quicker. Material costs are also reduced with respect to structural titanium parts that are machined from a billet or forged. The EBAM spare also all the required involved machining time by as much as 80%. Dennis Little, Lockheed's vice president of production for space systems, stated that, those manufacturing advantages involved in the 3D EBAM-printed titanium tanks, will be in use on spacecraft before the decade is out, provided that internal evaluation of the process meets certification requirements from the US Air Force and NASA.

4.5. 3D printed drones

Drone fashion hobby, also used in serious applications, has dramatically increased in the past several years. Global unit sales grew 60% (to 2.2 million) and revenue increased 36% (to $4.5 billion) in 2016 [26]. American consumers in the United States alone, bought 2.4 million hobbyist drones, compared to 1.1 million in the previous year. In 2017, revenue is anticipated to reach $6 billion, while units should rise up to 3 million. The latter figures substantiate a revenue growth of 39% and unit growth 34% within 2 years time, according to a study conducted by the research firm Gartner Inc. [27].

Impressively, engineers, designers, and other individual end-users become more and more involved in current research and development efforts to manufacture 3D-printed drones are now eligible for R&D federal and state tax credits.

Military sectors are intensively exploring novel paths to make cheaper, lighter, and more energy-efficient drones. A Marine Corp named Rhet McNeal created Scout, a drone composed of 3D-printed components. Scout only costs $600 to build. In comparison, a similar military-grade drone costs hundreds of thousands of dollars to build from advanced materials with conventional methods. Another benefit which arises from the technology, being a 3D-printed drone, should it receive any damage, any part or parts can be directly printed out and installed within hours. On the other side of the fence, a standard-issue drone would require weeks, sometimes months, to get a replacement through the Marine Corps' supply chain. Scout has been delivered to Mitre Corp., a USMC drone supplier, for certification testing. Prior to Scout, Mitre Corp. experimented with a 3D-printed drone called Nibbler. In the following period of time, the USMC is planning to test Nibbler into a real combat zone in order to supply troops with required resources. At the same time, they are investing resources in R&D on how to manufacture 3D-printed drones for surveillance purposes.

The University of Virginia, in its term, designed and created a 3D-printed UAV drone for the Department of Defense. The Drone can be printed in less than 24 h at an end-user price of $2500, electronics development included. The fuselage of the drone costs only $800. Resembling to one long wing, it was nicknamed the Razor. The Razor can fly at maximum speed of 40 mph for up to 45 min, having a gross weight at 6 pounds with all the equipment installed.

None of its features and capabilities is compromised by the fact that it is 3D-printed; in fact, it features all the same functions and operational capabilities as a typical military-grade drone, including GPS waypoints for navigation and mile-distance control. Even camera hoisting and phone linking capabilities that extend the distance it can be controlled are present. Being 3D printed, it has even greater advantage that it can be modified and reprinted by desire and need. It is fully customizable, as it can be made smaller or bigger, geared to carry a sensor instead of a camera, or fly slower or faster as each different operation requires.

Solid Concepts uses additive manufacturing to produce fixed-wing UAS airframes (such as the PTERA shown in **Figure 14**) that are used to test high-risk circulation control systems, conformal fuel tank concepts, and other advanced aerospace concepts with SLS 3D-printed parts.

4.6. 4D printing

Additive manufacturing—or 3D printing—is almost 30 years old. Today, it is not only just found in industry but also in households, as the price of high accuracy 3D printers has fallen below US$1000. Understanding of this new power enabling us to design and print almost anything in three dimensions, not just scribes and symbols on paper, opens up unlimited opportunities for everyday people to manufacture from toys and household appliances, to jewels and tools, in our homes and work places.

Well, guess again, there is even more that can be done with 3D-printed materials. We can make them more flexible and more useful. Smart structures can be also printed, featuring embedded sensors and actuators. These objects, also 3D-printed, can transform in a pre-programmed way in response to an external stimulus. Such a technology enabling objects, parts, or even complete systems to be manufactured was baptized by the popular science name of “4D printing.” Perhaps, it leads us to a better or easier way to think about that the object transforms or reacts over time.

Of course, such a behavior of structural deformations is not at all quite new. Researchers have been for decades researching and demonstrating “memory” and “smart material” effects and properties. In their recent Nature article, Raviv et al. propose a new design of complex self-evolving structures that vary over time due to environmental interactions [28]. Logically, in conventional 3D printing systems, materials are expected to exhibit a stable response rather than an active one and fabricated objects are designed and printed as static items or functional parts at the most. In this paper, a novel approach is introduced for simulating and fabricating self-evolving structures. These “smart” structures transform

Figure 14. 3D-printed military drone-PTERA of solid concepts.

into a predetermined shape, by changing properties and functions after fabrication has been completed. The new locally coordinated bending primitives combine into a single system, allowing for a global deformation which can stretch, fold, and bend in the given environmental stimulus. The physics of 4D printing often requires multiple materials to be embedded into a single 3D structure. Much work is anticipated to be invested on such 4D printers and structures over the next decades.

5. Conclusions

In our days, it is apparent that we experience a very large revolution as far as novel production techniques is concerned, in manufacturing structures by advanced layering techniques, processes widely known under the simplistic name of 3D printing, for the wide public. The truth is that this new kind of industrial revolution regarding manufacturing has not been completed yet. Although techniques for glass and ceramics similar to 3D printing are developed as these lines are written, no mature methods have been proposed yet. Moreover, upon completion of this revolution, which owes a lot to electronics, software (CAD), and computer technology, we will be able to manufacture almost all our products utilizing 3D printing or even 4D printing technologies for smart structures.

It is of course common sense that this will influence our way of thinking and designing items and parts or even whole devices at once, since results of simulation and design optimization are nowadays directly printable. Mankind will benefit, as already does, from applications ranging from medical equipment and implants, biomaterials, or biomedical devices, to possible automated orbital factories fully equipped with 3D printers for space exploration equipment. The limits for this new technology for manufacturing are far from being set as yet. Transport and automotive sectors are also supposed to profit from the impact of 3D printing technologies.

Since these techniques are saving energy and CO_2 emissions, and their products or by-products are recyclable too; it is also a revolution of green manufacturing. Furthermore, as scientists are moving into MEMS and NEMS device manufacturing techniques, it is certainly implied that in some future era, mankind will possess technology to perform atom by atom structuring. This has already been shown. From atom scale to nano-, micro-, and macroscale, we are almost able to manipulate matter totally.

Author details

Dionysios E. Mouzakis

Address all correspondence to: demouzakis@sse.gr

Department of Military Sciences, Hellenic Army Academy, Sector of Mathematics and Engineering Applications, Greece

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