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BOOSTING THE SCIENTIFIC EXCELLENCE AND INNOVATION CAPACITY OF 3D PRINTING METHODS IN PANDEMIC PERIOD

MODULE 5

3D PRINTING AND RAPID TOOLING

Project Title	**Boosting the scientific excellence and innovation capacity of 3D printing methods in pandemic period 2020-1-RO01-KA226-HE-095517**
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Authors	**Răzvan Păcurar, Nikola Vitkovic, Aleksandar Miltenovic**
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Content

1 Use of the 3D printing / Rapid Tooling methods for medical applications

3D printing and Rapid Tooling methods are nowadays more and more used in the field of medical applications. This domain is very dynamic, challenging and attractive in terms of new types of 3D printing methods, materials, software programs or applications. In the context of the pandemic, especially when new medical parts are required to be designed, developed, produced and tested in the health sector, there is a strong demand of involving people from different sectors that have high level of expertise in complementary fields, either we are referring to medicine, physics, chemistry or engineering domains (IT, manufacturing, etc). 3D printing in the pandemic period has raised the variety of products in order to support the needs from this period. Due to the advantages that 3D printing offers, medical devices (ventilator valves, emergency respiration devices, mask connectors), protective equipment (face shield, face mask, mask adjusters, door openers), testing devices (nasopharyngeal swabs), implants or 3D printed isolation wards have been developed and manufactured with the support of the universities and the SMEs in the last year. Based on the positive experience proved by the use of se methods on very practical basis, this module aims to provide different good practice examples of using these modern methods (3D printing and Rapid Tooling) with the aim of providing from the BRIGHT consortium own experience or other experiences right knowledge and skills in the developing process of new products, in accordance with hospitals / public society needs in the pandemic period. The main examples in using different types of 3D printing methods (Selective Laser Sintering, Selective Laser Melting, Fused Deposition Modeling, Fused Filament Fabrication, Stereolitography, etc) as well as Rapid Tooling methods (Vacuum casting or Metal Spraying) are presented in this module, emphasizing meanwhile the most advanced challenges and trends in this field, including the last achievements that were reached in the bio-medical 3D printing, multi-material 3D printing and 4D printing methods in the end.

2. Additive Manufacturing technologies

2.1. Multi Jet Fusion technology

2.1.1. Introduction. The Presentation of Multi Jet Fusion technology

The technology presented in this chapter is very recent and was developed exclusively by the company Hewlett Packard, a U.S. multinational company based in Palo Alto with more than 58 billion declared in 2019. The company (known simply as HP) is active in various fields related to information technology: it produces hardware (computers, servers, printers) and software. The innovation linked to the birth of Multi Jet Fusion technology is not the first linked to this company: the first multi-touch touch screen computer was born in 2009 and it was produced by HP. The company has always been a world leader in the production of printers: 3D printing technologies have always been at the center of the company's research until the birth of MJF technology.

2.1.2. The Working Principle of the Multi Jet Fusion technology

The announcement of the birth of Multi Jet Fusion technology by Hewlett Packard (with 3D printers model n. 4210 and 4200) has generated a lot of enthusiasm in the world of 3D printing, since this is an ideal technology to replace CNC or injection molding technologies.

In this paragraph the technology will be presented with the use of representative images. Multi Jet Fusion technology is based on powders (usually nylon) without the use of lasers. Initially the powder bed is heated uniformly and then a melting agent is deposited only at the points where it is necessary to selectively melt the particles.

Then a finishing agent is used to improve the resolution of the parts.

Fig 2.1. First stages of the Multi Jet Fusion technology [www 01]

The stages of the process are shown in figure 2.1. As one may notice in this figure, first, modeling software such as Autodesk Inventor or Solidworks or HP software are used to draw the part to be created using MJF. The second step takes place on the printer: the material (for example PA12) is placed on a table inside the printer and the printing chamber is heated to the next melting temperature of the material used. The melting and finishing agents are poured onto the bed of material to facilitate its selective melting: a print carriage with 3 print heads is used and the agents are deposited with a high resolution of 1200 dpi. After that, the printer lamps repeatedly pass over the surface and allow the jet material to capture and distribute heat.

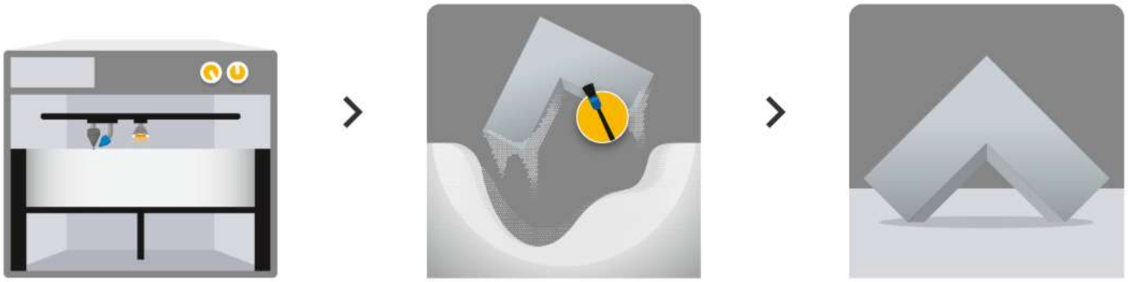


Fig 2.2. Latest stages of the Multi Jet Fusion technology [www 01]

After having worked and created a layer of material, the process continues for all the upper layers until the part is obtained (Multi Jet Fusion 3D printers use 340 million voxels per second) – see fig. 2.2.

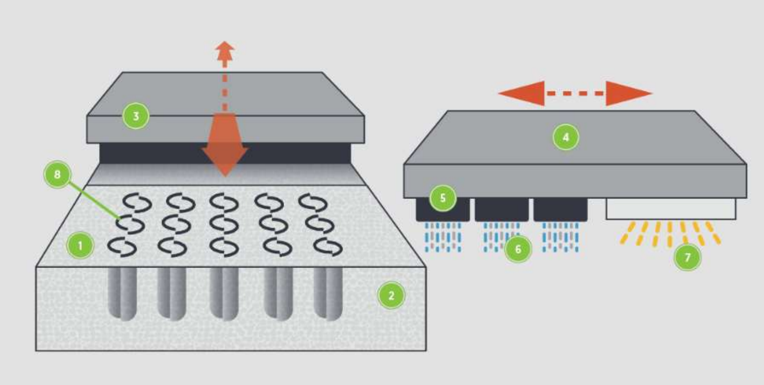


Fig 2.3. Printing process [www 02]

The printing process is shown figure 2.3. The characteristic elements are:

1) Nylon layer; 2) Powder' bed; 3) Material dispensing unit; 4) Print carriage; 5) Inkjet head; 6) Melting and finishing agents; 7) Thermal energy; 8) Part.

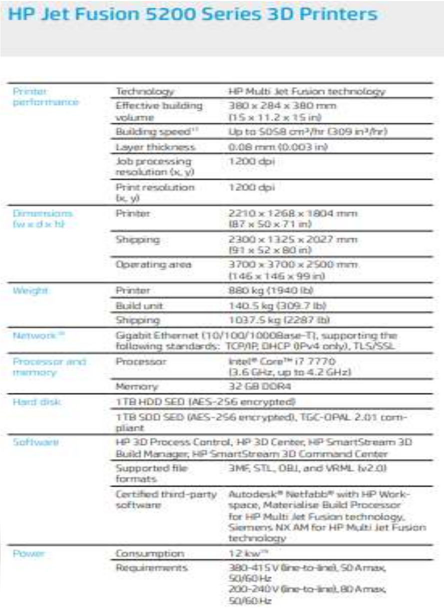
At this point the part is extracted and the material powders removed.

Finishing operations are carried out on the part before delivery to the user.

The surface is smooth at the exit of the printer: therefore the parts made with this technology require a minimal finish in post-production.

Multi Jet Fusion technology does not require support structures: this allows to increase the quality and reduce the final cost of the part. After the birth of technology, some companies started offering a printing service. These include Manufat Engeneering Srl, a company based in Lecco (IT): through the company's website it is possible to request technical advice. To do this, just load one or more Cad files respecting the printer operating parameters including the maximum volume 380x284x380 mm and minimal feature 1mm.

One model of the HP Multi Jet Fusion printer is the 3D Jet Fusion 5200 (fig. 2.4):



HP Jet Fusion 5200 Series 3D Printers

Printer performance	Technology	HP Multi Jet Fusion technology
	Effective building volume	380 x 284 x 380 mm (15 x 11.2 x 15 in)
	Building speed[11]	Up to 5058 cm³/hr (309 in³/hr)
	Layer thickness	0.08 mm (0.003 in)
	Job processing resolution (x, y)	1200 dpi
	Print resolution (x, y)	1200 dpi
Dimensions (w x d x h)	Printer	2210 x 1268 x 1804 mm (87 x 50 x 71 in)
	Shipping	2300 x 1325 x 2027 mm (91 x 52 x 80 in)
	Operating area	3700 x 3700 x 2500 mm (146 x 146 x 99 in)
Weight	Printer	880 kg (1940 lb)
	Build unit	140.5 kg (309.7 lb)
	Shipping	1037.5 kg (2287 lb)
Network[18]	Gigabit Ethernet (10/100/1000Base-T), supporting the following standards: TCP/IP, DHCP (IPv4 only), TLS/SSL	
Processor and memory	Processor	Intel® Core™ i7 7770 (3.6 GHz, up to 4.2 GHz)
	Memory	32 GB DDR4
Hard disk	1TB HDD SED (AES-256 encrypted)	
	1TB SDD SED (AES-256 encrypted), TGC-OPAL 2.01 compliant	
Software	HP 3D Process Control, HP 3D Center, HP SmartStream 3D Build Manager, HP SmartStream 3D Command Center	
	Supported file formats	3MF, STL, OBJ, and VRML (v2.0)
	Certified third-party software	Autodesk® Netfabb® with HP Workspace, Materialise Build Processor for HP Multi Jet Fusion technology, Siemens NX AM for HP Multi Jet Fusion technology
Power	Consumption	12 kw[19]
	Requirements	380-415 V (line-to-line), 50 A max, 50/60 Hz 200-240 V (line-to-line), 80 A max, 50/60 Hz

Fig 2.4. 3D Jet Fusion 5200 and its data sheet [www03]

The printer allows achieving perfect texture repeatability and unmatched cost-effectiveness. The sale of the printer is often combined with the sale of a software for the realization of the parts: among the software available on the HP catalog there are the HP 3D Process Control, the HP 3D Center and the HP SmartStream 3D Build Manager (intuitive software and that allow remote control of the printer) but it’s possible to use Autodesk Netfabb or Siemens NX Am anyway. A cooling system has also been developed by HP (fig. 2.5): this is important to remove and cool each element naturally and allows production without interruption, therefore increases productivity.

Fig 2.5. Cooling system [www04]

All technical data of the HP Jet Fusion 5200 can be found on the product presentation brochure (fig. 4.3). In figure 4.3 are given the most important characteristics of the printer, such as the effective building volume – 380x284x380 mm - (therefore the parts produced cannot be larger than this volume due to dimensional limits), the working speed – up to 5058 cm3/h - (index of productivity), the thickness of the layers – 0.08 mm - (quality index of the finished product) and the resolution – 1200 dpi. In addition there are some useful dimensions (printer dimensions or operating area) to help the company to correctly insert the printer in the corporate environment. The Intel Core I7 processor and 32 GB memory are useful to ensure the printer speed in processing information and sufficient storage space.

2.1.3. Examples of parts realized by the Multi Jet Fusion technology

The covid-19 has literally upset the lives of European citizens since March 2020, forcing several countries to lockdown. Several hospitals have run out of medical devices such as valves and ventilators, which are essential for fighting the epidemic and saving lives. The European Association for Additive Manufacturing is responding to a request from the European Commission and is asking the various members to work towards the production of medical equipment that can be used to treat Covid patients.

The companies that manufactured the valves faced two problems:

1) face potential legal actions by the companies owning the patent;

2) require a temporary waiver of the requirements of the Medical Devices Directive by the Member States.

The first area affected in Europe was Lombardy, in Italy. In particular, a hospital in Brescia quickly exhausted the respiratory valves needed to connect patients to machines.

The original patent owner “Intersurgical” was unable to respond to the sudden increase in demand. Luckily "Isinnova", a start-up company based in Brescia, Italy, intervened: the engineers Fracassi and Romaioli created a prototype, tested it on a patient and made several valves in series with the collaboration of another local company, Lonati from Brescia – Italy.

Isinnova is a start-up formed by a young and heterogeneous team of engineers, designers and communication experts who collects ideas of all types and sectors and transforms them into concrete objects. Usually the start-up is aimed at companies and individuals who have an innovative idea and want to turn it into a finished product.

The Isinnova site already has more than 80 projects carried out and 52 patents filed.

10 patients were accompanied in breathing by a machine with the use of a valve molded by Isinnova after just one day.

Fig 2.6 Original valve and 3D printed valve [www05]

The figure 2.6 shows the original valve (left) and its 3D printed cufflink (right).

The realization of the valves took place with the use of the powder bed fusion technology that offers numerous advantages such as high production speed (so reduction of time-to-market) up to 10 times compared to Selective Laser Sintering (SLS), reduced production costs, easy realization of complex parts and quality and performance of the components (tolerance min 0.1 mm). The reduction in production costs is linked to the reduction of waste with a reuse of powders up to 80 %.

Multi Jet Fusion technology also guarantees the materialization of parts with high density (1.01 g/cm3 if made of PA12) and low porosity (ratio between cavity volume and total volume). But not only the small Italian companies have mobilized against Covid-19: the Italian supercar manufacturer Ferrari has also started producing respiratory valves in its factory in Maranello, Emilia Romagna in Italy.

Ferrari, company which was founded in 1947, produces high-end sports cars and is the most titled in the Formula 1 World Championship (16 titles): it is currently part of the Fiat Chrysler Automotive FCA group and has 3200 employees worldwide as well as a turnover of 4 billion euros.

Ferrari has partnered with Novamacut, its supplier of multijet fusion systems from Bologna (Italy), and Solid Energy, a company from Cento (Italy). In addition, the valves have been developed by Mares, a manufacturer of diving equipment from Rapallo – Itay, in order to materialize emergency masks.

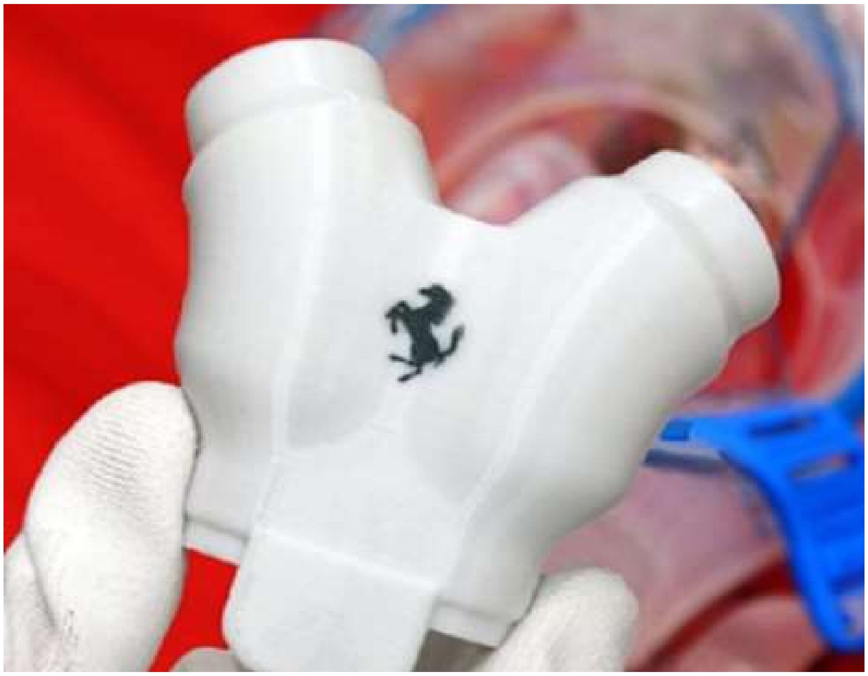


Fig 2.6. Valve produced by Ferrari [www06]

Obviously the valves produced by Ferrari with the historic "Cavallino rampante" logo (see Fig.2.6) were used in hospitals in northern Italy during the toughest phase of the emergency.

2.2. Fused Deposition Modeling

2.2.1 Introduction. The Presentation of Fused Filament Deposition (FDM) technology

Fused Deposition Modeling is one of the most used 3D printing technological method in the field of medical applications. *Stratasys* is a company which sells and produces 3D printed parts for other manufacturers. Stratasys method is Fused Deposition Modeling (FDM). The company has been created in 1989 by S. Scott Crump in the United States in Minneapolis. This company has over 500 employees and its turnover is more than 636 million of dollars. This company has its headquarters in Eden Prairie in United States and is in lots of different countries such as Brazil, Chile, Germany, India, Indonesia, China, Australia and Japan. The materials used for 3D printing are thermoplastic polymers such as ABS, PPFS, Nylon, PC and carbon fibers. The field of application for Stratasys equipment is aerospace, automotive, dental, medical, education, railway, art and Fashion. The most famous customers of Stratasys are Volvo, Ford, Honda, Airbus, Audi, Siemens and Google.

2.2.2 The Working Principle of the Fused Deposition Modeling (FDM) technology

The Fused Deposition Modeling starts by creating a 3D model of the part, using CAD software. Pre-processing- the STL file of the part is imported in a slicing software. In this stage the part is cut into multiple and horizontal layers with the thickness between 0.05mm and 0.4mm [www07], in case of PEEK/HA is recommended a value between 0.1mm and 0.3mm. For the part presented in Fig. 2.7 are necessary the supports during the FFF process. The supports are required because the material needs sustaining of the part in some areas while the part is being built from the bottom to the top. Referring on the vertebral body implant that must be realized, in the figure 2.7 is marked an example of area where the supports are needed.

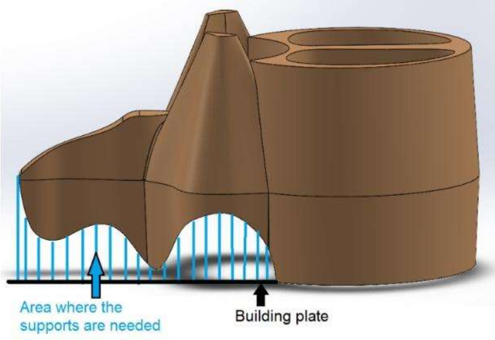


Fig. 2.7. Example of area where the supports are necessary

The software will generate automatically the support structure. For the supports is recommended to use a Polyvinyl alcohol (PVA) filament because is soluble in water.

The process of FDM printing is presented in figure 2.8. The PEEK/HA filament with the diameter of 1.75 mm (standard diameter) is rolled on a spool and is pulled by a stepper motor between the guide rollers. When the filament reaches the heating chamber (heated using an electrical coil heater) it is heated and reaches a temperature close to the melting temperature, but does not reach the melting temperature. [www08]

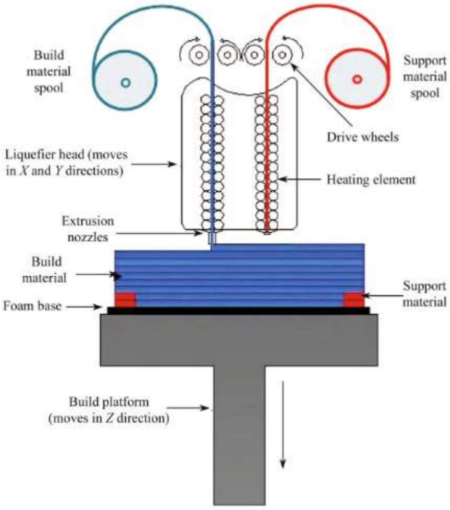


Fig. 2.8. Schematic representation of Fused Deposition Modeling technology [OMA15]

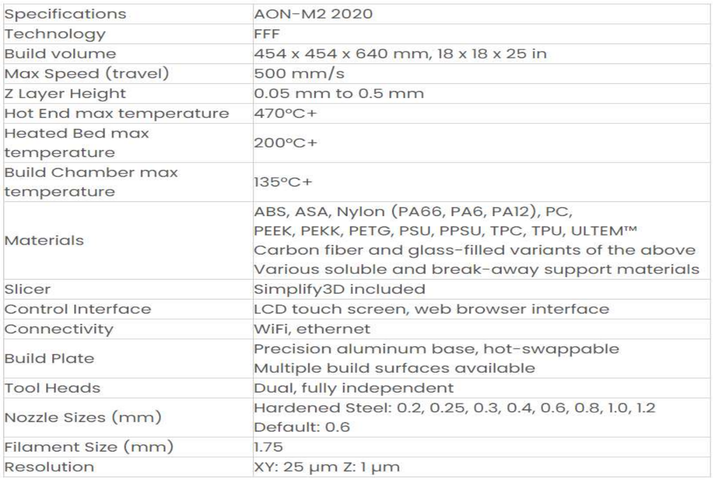
The liquid material passes through a nozzle with a diameter of 0.4mm (for PEEK/HA) and is deposited on the building plate. Also, the building plate is heated, using an electrical coil heater, in case of PEEK/HA at 100^0C, needed to enhance the part adhesion on the building plate and also is a smaller temperature than the temperature of the liquid material to allow the liquid material to solidify. In case of PEEK/HA the nozzle temperature is 390-400^0C. The temperature is continuously controlled by a sensor (thermocouple) positioned in the heating zone of the chamber. In order to obtain the desired shape of the part, the nozzle and the heating chamber (heating element from the heating zone) is moving on the X-Y axis, this motion being realized with the help of a stepper motor. When the layer is completed, the machine table is lowered in the Z direction with the thickness of a layer, also with the help of a stepper motor in order to start the next layer. These steps are repeated until the part is completed. For the supports it is a second system with PVA filament spool stepper motor, and nozzle that is heated up to 180^0C and the principle of printing is the same. When a layer of the part is completed, the support layer is deposited and after this the platform will go lower on the Z axis and starts the deposition of the next layer of the part. [www08]

When the part is finished it could be easily removed from the machine table and the supports are removed manually by introducing the part in warm water. Because the supports are made of PVA they will dissolve in water, obtaining only the piece from PEEK / HA. [www08]

2.2.3 Presentation of the companies which are developing equipment items for the Fused Deposition Modeling (FDM) Technology

AON3D is a company situated in Montreal, Canada and is a part of the Printing Machinery and Equipment Manufacturing Industry. The company produces the AON-M2 2020 equipment that offers 3D printed parts with high-performance of thermoplastics materials. The equipment could use materials like Polycarbonate, ULTEM 9085, Aquasys, PEEK, PEEK and Carbon Fiber PEEK, PEKK and Carbon fiber PEKK. Because the equipment is capable to print parts made of PEEK filament it is suitable for PEEK and HA filament. This can be said because the content of HA in the PEEK filament does not influence the printing parameters.
The AON3D company offers support for the full-cycle of 3D printing, this include the 3D model and the printed final part. [www09] Apium is a company situated in Karlsruhe, Germany that provided and developed the first commercially PEEK filament for FDM technology. The company offers solutions for high performance metals and polymers in the

precised technology. The products made by Apium are two types of 3D printers (Apium P220, Apium M220), a filament dryer (Apium F300 Filament Dryer) and different types of filaments based on (PEEK, PEI, PVDF, PP, PEKK, ABS and Vestakeep-for medical devices and implants). Vestakeep is a special filament for medical industry, based on PEEK. Regarding Vestakeep filament and the fact that the content of HA in the PEEK filament does not affect the printing parameters it could be said that the Apium 3D printers are suitable for PEEK and HA filaments. [www10]



Specifications	AON-M2 2020
Technology	FFF
Build volume	454 x 454 x 640 mm, 18 x 18 x 25 in
Max Speed (travel)	500 mm/s
Z Layer Height	0.05 mm to 0.5 mm
Hot End max temperature	470°C+
Heated Bed max temperature	200°C+
Build Chamber max temperature	135°C+
Materials	ABS, ASA, Nylon (PA66, PA6, PA12), PC, PEEK, PEKK, PETG, PSU, PPSU, TPC, TPU, ULTEM™ Carbon fiber and glass-filled variants of the above Various soluble and break-away support materials
Slicer	Simplify3D included
Control Interface	LCD touch screen, web browser interface
Connectivity	WiFi, ethernet
Build Plate	Precision aluminum base, hot-swappable Multiple build surfaces available
Tool Heads	Dual, fully independent
Nozzle Sizes (mm)	Hardened Steel: 0.2, 0.25, 0.3, 0.4, 0.6, 0.8, 1.0, 1.2 Default: 0.6
Filament Size (mm)	1.75
Resolution	XY: 25 μm Z: 1 μm

Fig. 2.9 AON-M2 2020 equipment and characteristics of this equipment [www09]

In figure 2.9 is presented the AON-M2 2020 equipment made by the AON3D company and its main characteristics. The equipment uses the FDM technology in order to print different parts. The building volume on this equipment is 454x454x640 mm. Maximum speed that could be achived is 500mm/s. The maximum temperatures for its components are: 4700C for the hot end, 2000C for heated bed and 1350C for the build chamber. For PEEK/HA the hot end recommended temperature is about 390-4100C and the bed recommended temperature is 1000C. AON-M2 2020 is capable to use different nozzles with different size between 0.2 and 1.2mm. Also, the layer thickness is between 0.05 and 0.5mm. [www09] The recommended size for the nozzle, for PEEK/HA is 0.4mm and the recommended layer thickness is between 0.1 and 0.3mm. The filament size should be 1.75mm (it is a standard value for filaments) and the resolutions are XY: 25µm, Z: 1µm.

The FDM technology requires slicing the 3D model, so the equipment has a program for this operation, called Simplify3D. Another important characteristic is that the equipment is capable to print in the same time two identical parts or printing one part using two different materials. [www09]

Model	P220
Brand	Apium
Max. build size	220 × 175 × 160 mm
Max. build volume	6.16 L
Max. temperatures	
Extruder	540 °C
Build chamber	180 °C
Build plate	160 °C
Min. layer thickness	0.1 mm
XY accuracy	0.0125 mm =12.5 µm
Nozzle diameter(s)	0.4 mm
Filament diameter	1.75 mm

Fig. 2.10 Apium P220 equipment and specifications [www10]

In figure 2.10 is presented the Apium P220 equipment made of Apium company and its main characteristics. The equipment uses the FDM technology in order to print different parts. The building volume on this equipment is 220x175x160mm. The maximum temperatures for its components are: 5400C for the extruder, 1800C for build chamber and 1600C for the build plate. [www10] For PEEK/HA the extruder recommended temperature is about 390-4100C. The nozzle of this equipment has a diameter of 0.4mm and the minimum layer thickness is 0.1mm. The recommended size for the nozzle, for PEEK/HA is 0.4mm and the recommended layer thickness is between 0.1 and 0.3mm. The filament size should be 1.75mm (it is a standard value for filaments), the XY accuracy/resolution is 12.5µm and Z resolution is 50µm.

An important characteristic of this equipment is that it was specially designed for PEEK filaments. The equipment was developed for printing parts of PEEK material, so the nozzle diameter could be only 0.4mm (recommended value for PEEK). Maximum temperatures that the equipment could reach are bigger than the temperatures needed for printing parts made of PEEK because the equipment is capable to print parts made of another type of materials (for example PVDF, Smart ABS), but the equipment could reach the needed temperatures for PEEK parts. [www10]

2.2.4 Examples of parts made by FDM technology

Medicrea Group is a French company, located in Lyon city, specialized in the field of spinal pathologies. They use the fused deposition modeling in order to print spinal implants. The first UNiD implant was made of polyetherketoneketone (PEKK) but they are currently making implants of polyetheretherketone (PEEK) (Fig. 2.11).[www11]

Fig. 2.11. 3D printed UNiD ALIF cage implants [www11]

The UNiD ALIF inter-somatic anatomical inter-body device was developed by Medicrea from a 3-D digital file created from the extraction and treatment of pre-operatory scanner images of the patient, a process developed internally by Medicrea's R&D teams. Using a customized spine cage, Vincent Fiere performed the surgery at the Hospital Jean Mermoz.

PEEK is a biomaterial and was first developed by a group of English scientists in 1978 [PHI18]. PEEK is a semi-crystalline thermoplastic with excellent mechanical and chemical resistance properties that are retained to high temperatures. The Young's modulus is 3.6 GPa and its tensile strength 90 to 100 MPa. These characteristics are important from the point of view of the implant's functionality, it is necessary for the implant to support a person's body weight. PEEK has a glass transition temperature of around 143 °C (289 °F) and melts around 343 °C (662 °F), temperatures that are needed in the FDM process, for knowing how to set the process parameters (more precisely, the temperature of the chamber, nozzle and the building plate). [www12] The commercial name for PEEK used in medical industry is PEEK OPTIMA.

For improving the biocompatibility and the bone repair, the PEEK material was combined with HA (Hydroxyapatite). The commercial name for the material composed by PEEK and HA si PEEK OPTIMA HA.

Victrex is a company based in United Kingdom, Thornton Cleveleys and works on two domains: one for automotive, aerospace and electronics industry and one for medical industry. For the medical industry they made Invibio, it is the name of the branch dealing with materials and solutions for the medical industry. [www13] Victrex company show that vertebral implants could be made from PEEK OPTIMA HA, and in figure 2.12 is presented one of their type of spinal implant.

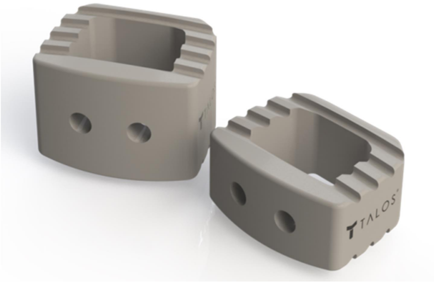


Fig. 2.12 Spinal implant made of PEEK OPTIMA HA [www13]

According to Invibio, the implants made of PEEK OPTIMA HA are better than the implants made of PEEK OPTIMA because of the presence of HA. HA has similar structure with the bone and this help for the osteoconductivity and make the implant more body friendly. HA contain calcium and phosphate, components that are present in bone structure. Also, the crystallinity structure of HA gives a non-resorbable character that is essential in the spinal surgery because there is no risk for diseases transmission. [www14]

Also, Invibio made an analysis comparing the implant of PEEK OPTIMA with one made of PEEK OPTIMA HA. It was concluded that after four weeks in case of PEEK OPTIMA HA the contact with the bone increased with 75% compared to PEEK OPTIMA and after twelve weeks starts the bone apposition (Fig. 2.13). [www14]

Fig. 2.13. Bone apposition [www14]

They made CT scans at six and twelve weeks (Fig. 2.14) and they observed that in case of PEEK OPTIMA HA was a better grow of bone. The bone was grew on all surfaces of the implant, which relieves patients' pain. [www14]

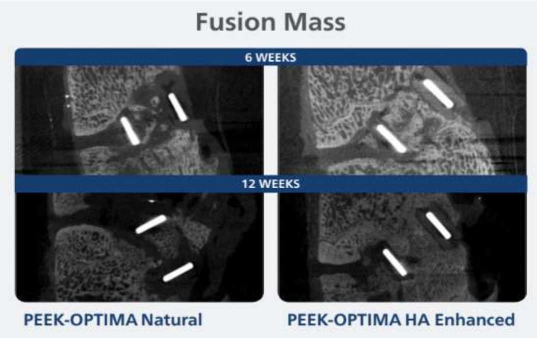


Fig. 2.14 CT at 6 and 12 weeks [www14]

Invibio conclude that the HA does not change the properties of the PEEK material (there are not different properties between PEEK OPTIMA and PEEK OPTIMA HA), the difference being only in the bone repair, HA making a big difference after the surgery.

2.3. Fused filament fabrication

2.3.1 Introduction

3D printing Carbon Fiber is based on the same working principle as FDM additive manufacturing with few peculiarities. The process is made based on layer by layer adding principle, but as compared to the classical FDM technology, through a filament made of nylon plastic material, of 1.75 mm diameter bound with the carbon fiber material. The nozzle is moving on the x-y plane the path being determined by the computer design of the model. Markforged is an industrial company that prints industrial parts by using Continuous fiber fabrication (CFF) method. Founded in 2013 and based in Massachusetts, Markforged has about 250 employees globally, with $137 million in both strategic and venture capital. This company is located in a lot of countries across the world like United States, Canada, Brazil, Europe (France, Spain, United Kingdom, Portugal, Italy, Germany, Norway, Sweden and Russia), South Africa, India, China, Japan, Indonesia, Australia and the materials which can be used for the technology assigned are metallic (like Stainless stee), composite base materials (like onyx which is a micro carbon fiber filled with nylon) or nylon) and continuous fiber (like carbon fiber, Kevlar or fiberglass). The field of application for Markforged equipment are the industries, automotive, industrial equipment, product development, aerospace, federal and defense, energy, education, electronics manufacturing and medical. Stratasys is a company which sells and produces 3D printed parts for other manufacturers. Stratasys method is Fused Deposition Modeling (FDM). The company has been created in 1989 by S. Scott Crump in the United States in Minneapolis. This company has over 500 employees and its turnover is more than 636 million of dollars. This company has its headquarters in Eden Prairie in United States and is in lots of different countries such as Brazil, Chile, Germany, India, Indonesia, China, Australia and Japan. The materials used for 3D printing are thermoplastic polymers such as ABS, PPFS, Nylon, PC and carbon fibers. The field of application for Stratasys equipment is aerospace, automotive, dental, medical, education, etc.

2.3.2. Working principle of Fussed Filament fabrication

3D printing Carbon Fiber is based on the same working principle as FDM additive manufacturing with few peculiarities. The process is made based on layer by layer adding principle, but as compared to the classical FDM technology, through a filament made of nylon plastic material, of 1.75 mm diameter bound with the carbon fiber material. The nozzle is moving on the x-y plane the path being determined by the computer design of the model.

In Fig 2.15 is presented the process 3D printing, FDM. The plastic filament can be (PLA, ABS, PA etc.) which is pushed by a feeder into the nozzle (the material are heated inside the nozzle at a temperature of 170-180°C, the materials are heat inside the hot block and the heater is the one that controls the temperature .

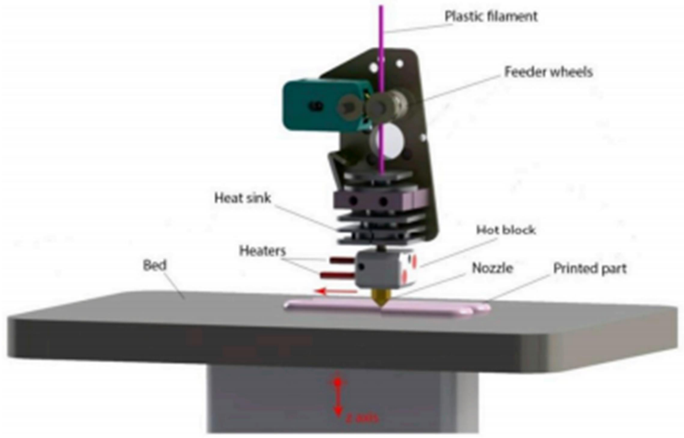


Fig 2.15. Schematic of FDM 3D printer used for parts made of CF [HEI19]

The carbon fibers are going through a hot block of stainless steel, the filaments are rolled with the help of the feeder wheels in the nozzle the carbon fiber and the melted nylon are in contact. Inside the nozzle is to entries gaps from where the plastic and carbon filament enter inside the nozzle, the feeder wheels are the ones that guide the material through the nozzle. The nozzle is moving with the help of the motor which lead the printing head on XY axis and the other motor that control the working plate on Z axis. The printing head is moving through a path in order to obtain the shape and the working plate is moving in order to obtain the height of the part. The fiber orientation is made by the program, the machine follows the program and is moving the printing head, program which is followed by the printing head, the motion is controlled and the printing head is moving along a path that is determined by the 3D computer aided design, the program that was used for dividing the layers being called "slicer".

The fibers can be from 100 to 500µm of diameter 7.2 µm). The temperature of the materials is at 170-180 °C. After the first layer is finished, the material is deposited by the printing head which is moving on XY axis, before the second layers is applied the working plate is moving on z axis down with the dimension of one layer. In Fig 2.16 are presented the components of the extruder. As one may notice in this Figure, the extruder has two gaps from which the materials enter inside the nozzle, one from which the plastic filament enter and one for the carbon fiber, the two materials meet in a hot block (heated by 2 heaters) and then are laid out onto the bed, making the layer for the composite part. The feeder wheels are the ones that move the material through the nozzle. The nozzle is moving on XY axis and the working plate on Z axis. For a better roughness of the surface machinability can be performed on the surface with a milling machine. The supports are soluble in water or the part doesn't required supports.

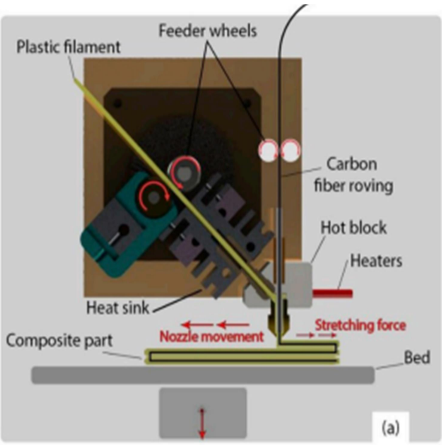


Fig 2.16. Schematic of the novel designed extruder [HEI19]

2.3.3. Fussed Filament fabrication equipment items

The Stratasys company has developed machines specifically designed for carbon fiber 3D printing. The chosen machine for the printing of a rear wing of a formula one is the Fortus 450mc as shown in figure 2.17.

As shown in Fig. 2.17 the Fortus 380mc offers a sized build chamber to build prototypes, end-use parts and tooling in a production environment. The Fortus 380mc is designed with an intuitive touchscreen interface for an efficient workflow of the data information. The main technology used is FDM method. There is one nozzle on this machine. High performance materials can be printed thanks to Fortus 380mc such as Nylon 12CF (carbon fiber). As the parts of the Formula 1 rear wing are very large and the capacity of the 3D printer is limited as presented in figure 4.6, they will have to be printed in several times.

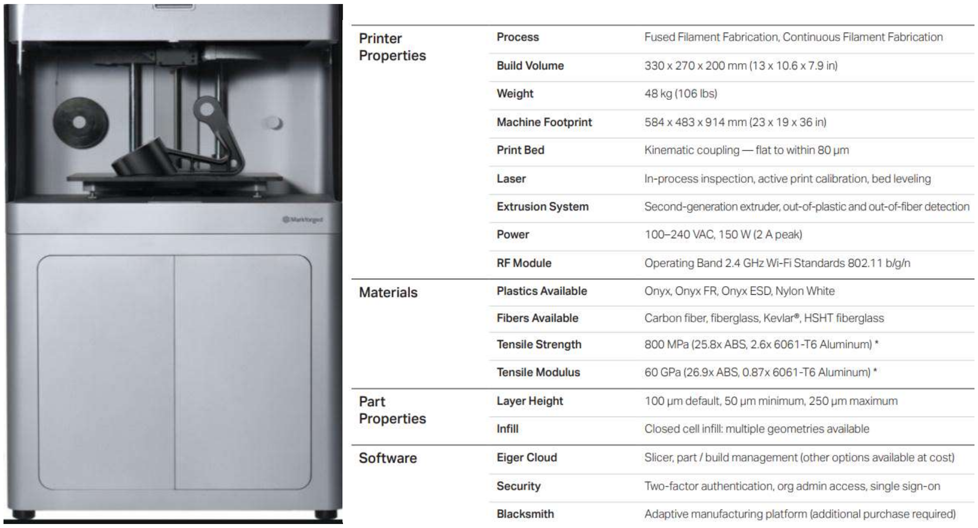
System Specifications	
System Configuration	
Build Envelope (XYZ)	355 x 305 x 305 mm (14 x 12 x 12 in.)
Material Delivery	One bay each for material and support canisters

Material Options						
Material	**Layer Thickness**				**Support Structure**	**Available Colors**
	0.330 mm (0.013 in.)	0.254 mm (0.010 in.)	0.178 mm (0.007 in.)	0.127 mm (0.005 in.)		
ASA	●	●	●	●	Soluble	■ Black ■ Dark Gray ■ Light Gray □ White ■ Ivory ■ Dark Blue ■ Green ■ Yellow ■ Orange ■ Red
FDM Nylon 12CF		●			Soluble	■ Black

OTHER SPECIFICATIONS	
System Size and Weight	129.5 cm x 90.2 cm x 198.4 cm (51 x 35.5 x 78.1 in.); 601 kg (1,325 lbs.)
Achievable Accuracy	Parts are produced within an accuracy of ± .127 mm (± .005 in.) or ± .0015 mm/mm (± .0015 in/in), whichever is greater). Z part accuracy includes an additional tolerance of -0.000/+slice height. Note: Accuracy is geometry dependent. Achievable accuracy specification derived from statistical data at 95% dimensional yield.
Network Communication	10/100 base T connection. Ethernet protocol.
Operator Attendance	Limited attendance for job start and stop required.
Power Requirements	208VAC 3 phase, 50/60 Hz, 18 Amps
Regulatory Compliance	CE, cTUVus, EAC, FCC Part B
Software	All Fortus® systems include Insight and Control Center job processing and management software. Compatible with GrabCAD Print for use with job reports, scheduling and remote monitoring.
Operating System	Microsoft Windows 10 (Pro, Enterprise, Education), Microsoft Windows 8.1 and Windows 8 (Pro, Enterprise), Microsoft Windows 7 (Pro, Enterprise, Ultimate), Microsoft Windows Server 2012 R2. Insight software requires a 64-bit operating system.

Fig. 2.17. Fortus 380mc Carbon Fiber Edition and main characteristics of this type of equipment [www15]

The accuracy for carbon fiber material is plus or minus 127mm and 0,0015mm. Markforged company has also developed machines for 3D printing carbon fiber. In order to correctly print parts, the recommend machine form Markforged is the X7 CFR as shown in picture 2.18 This machine can print parts with different materials such as Carbon Fiber, Onyx, Nylon, Fiberglass or Kevlar. The printing process is called Continuous Fiber reinforcement (CFR). As shown in Fig. 2.18, the Markforged X7 CFR printer offers a sized build chamber to build prototypes, end-use parts and tooling in a production environment. High performance materials can be printed thanks to Markforged X7 CFR such as carbon fiber, nylon or onyx. The machine made 50x faster and 20x cheaper parts, this advantage being available only on X7 machine. Building speed is more than 280 mm/s in this case. This machine offer a Turbo print feature, the system can print parts faster by increasing the speed and this does not affect the dimensional accuracy of the parts, making carbon fiber parts easier and faster, increasing the productivity but keeping the quality of the final part. [MAR21]The printing resolution on Z axis is of 50µm. The accuracy of the parts made with Markforged X7 is of ±250 µm.

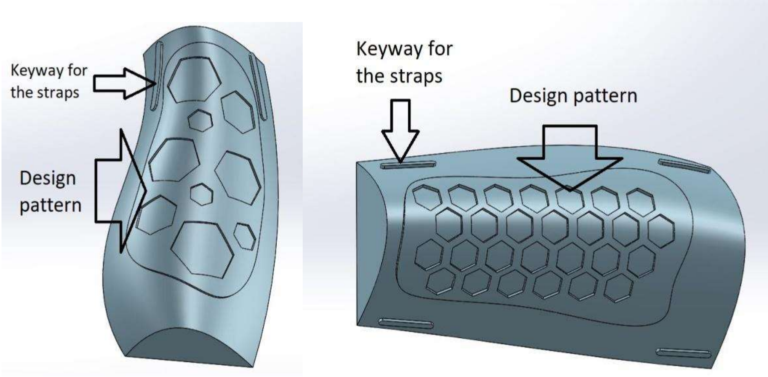


Printer Properties	Process	Fused Filament Fabrication, Continuous Filament Fabrication
	Build Volume	330 x 270 x 200 mm (13 x 10.6 x 7.9 in)
	Weight	48 kg (106 lbs)
	Machine Footprint	584 x 483 x 914 mm (23 x 19 x 36 in)
	Print Bed	Kinematic coupling — flat to within 80 μm
	Laser	In-process inspection, active print calibration, bed leveling
	Extrusion System	Second-generation extruder, out-of-plastic and out-of-fiber detection
	Power	100–240 VAC, 150 W (2 A peak)
	RF Module	Operating Band 2.4 GHz Wi-Fi Standards 802.11 b/g/n
Materials	Plastics Available	Onyx, Onyx FR, Onyx ESD, Nylon White
	Fibers Available	Carbon fiber, fiberglass, Kevlar®, HSHT fiberglass
	Tensile Strength	800 MPa (25.8x ABS, 2.6x 6061-T6 Aluminum) *
	Tensile Modulus	60 GPa (26.9x ABS, 0.87x 6061-T6 Aluminum) *
Part Properties	Layer Height	100 μm default, 50 μm minimum, 250 μm maximum
	Infill	Closed cell infill: multiple geometries available
Software	Eiger Cloud	Slicer, part / build management (other options available at cost)
	Security	Two-factor authentication, org admin access, single sign-on
	Blacksmith	Adaptive manufacturing platform (additional purchase required)

Fig 2.18 Markforged X7 CFR printer and main characteristics of this type of equipment [www16]

2.3.4. Examples of parts made by FFF technology

An example, it is presented the optimization from manufacturing process (Fig 2.19) for adding inserts to the mold. The inserts are fixed on the mold with socket screws and ties. By tightening the screws, the tie presses the insert in the mold and the hexagonal shapes are filled with material. [www16]



(a) Upper arm insert (b) Lower arm insert

Fig 2.19. Optimization of manufacturing process for the hexagon shapes of the mold

The first example, is a custom prosthetic prototype realized by Fused Filament Fabrication – 3D printing. The material of the part it is a micro carbon fiber filled nylon named by the company "Onyx". This material has very good yield properties, offers high strength, high resistance to different types of stress and can be reinforced with continuous fibers when yielded. The Onyx material is Markforged patent composite base material. Markforged company headquarters are based in USA Massachusetts, Sao Paulo, Toronto Canada and Tokyo. Onyx has a large field of usage, for example in the aerospace and defense industry, medical, electronics, housing and product development. The good finish quality and mechanical characteristics provide a longer durability of the parts usage, a better wear resistance (not friction wear). There are two more types of Onyx materials: Onyx FR – used in applications where parts must be non-flammable, and Onyx ESD – has a tight range of surface resistance. The flexural strength of the Onyx material is 71 MPa and the heat deflection temperature is 145 °C. These properties make the prosthetic prototype a very good example of the Onyx use. Normally, when a human has different problems with it's limbs, had an injury or amputation, a prosthetic limb is the solution. This prototype enhances the materials quality by combining it with some electrical circuits and new technology (sensors) to replicate the natural movements of a human hand (movement and grabbing actions).

A second example of 3D printed part using the FFF/FDM technology is shown in Fig. 2.20. The orthosis show below, are prototype parts from the Stratasys company. The company has the headquarters in the United States, but also has branches also in Israel, North America, Germany, Japan, Korea, China and Mexico. Stratasys uses for their prototype and studies of tensile, flexural and other types of load stress a material based on Nylon 12 reinforced with carbon fiber. "Nylon 12CF" provides a cleaner carbon fiber additive process than SLA with equivalent or even better strength properties. This material offers the strength and rigidity to replace even metal in certain cases or applications. Using the properties of layer by layer deposition, designers and engineers can be more creative and use, in some cases, the part in the same day as the concept finish. Tensile strength for the Nylon 12CF material is around 75 MPa, and the flexural strength is about 140 MPa compared to Nylon by itself which has tensile strength equal to 42 MPa and a flexural strength of 67 MPa. The large variety of properties and concept freedom does enhance a large field of use for the composite material such as the aerospace industry, automotive, medical, prototyping, dental, education, railway, etc. Offered by the Stratasys Company, there are a few printers which can print this type of material, for example the most compatible printer is the Fortus 450MC.

Fig. 2.20. Orthosis prototype parts from the Stratasys company [www17]

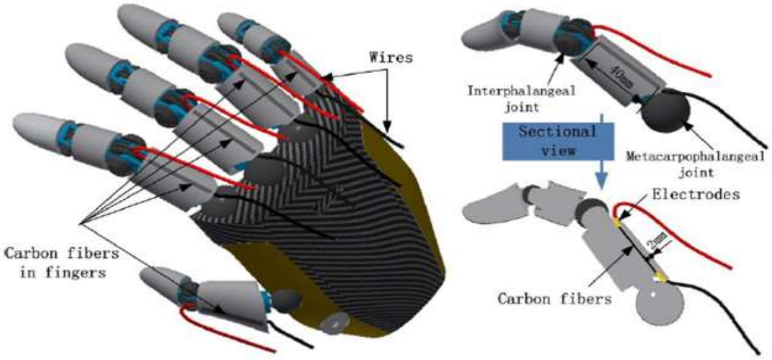


Fig. 2.21. Robotic orthosis [XIN17]

Additive manufacturing technology has recently been applied in the field of prosthetics, it enables the possibility to manufacture products for the disabled, such as limb prostheses, ankle-foot orthoses, robotic running feet and legs, and femurs. Because the 3D printed structure reinforced with carbon fiber shows great improvement in strength and self-perception of structural health, artificial hand based on carbon fiber are manufactured as a demonstration and to evaluate the use of carbon fiber as a structural reinforcement material. In figure 10 is presented an overview of the carbon fiber embedded 3D printing concept of artificial hands. The carbon fibers are placed in five fingers during the manufacturing process, and the ends of the carbon fibers are connected to electrodes composed of silver paste and enameled wire. [XIN17]

2.4. Selective Laser Sintering

2.4.1. Introduction. The Presentation of the SLS technology

Selective Laser Sintering (SLS) is an Additive Manufacturing (AM) innovation that utilization a powerful laser to materialize components in the medical industry such as hand prostheses. Hand prostheses can be made easily with SLS printing process due to the complexity of the piece and the simplicity of the process. These elements are much more suitable to be manufactured by SLS because the process produces functional assembly prototypes. Also, the process does not require other operations such as drilling and milling hard-to-reach areas as in the case of molds because it can easily produce them and for an entire manufacturing process you need qualified personnel for each process.

3D Systems Corporation is the first company that produced the SLS systems in the world. The company was founded by Charles W. Hull and Raymond S. Freed, in 1986. DTM Corporation started to commercialize SLS principle in 1987, and the first commercial machine they produced was in 1992. They were the only one company that had worldwide license, until August 2001, when 3D Systems bought the license. They are specialized in many industries, including aerospace, automotive, healthcare, dental and entertainment using polypropylene-like materials too(e.g. PA2200, with the ultimate tensile strength of 48MPa and bend strength of 58 MPa). EOS is also one of the leader companies in the world for 3D printing and additive manufacturing, this company is dealing with additive manufacturing with metals and plastics material in aerospace, orthoses, dental and medical technologies. This German company applies polymer materials like PA2200 (Polyamide 12, nylon), PA2001, PA2202 black, for producing parts in the medical field like orthoses and prosthetics with limitless customizations, increasing comfort by creating more elastic part with breathable designs.

2.4.2. The Working Principle of the SLS technology

Manufacturing of SLS parts are widely used in different range of industry: automobile, aerospace and even for medical applications for producing human body reconstructions and customized medical implants. The principle of working of SLS technology is presented in figure 2.22. In Selective Laser Sintering technology the parts are built up layer by layer. Prior to the start of the manufacturing process, the stock powder is heated at a temperature with few degree under the melting point of the material.

The manufacturing process has 3 main steps:

- the platform lowers with the thickness of one layer,
- the levelling roller is distributing the powder onto the build platform
- the laser is scanning the shape of the layer

Under the laser, the powder is melting and a solid layer of the part is obtained. These steps are repeated until the parts are completed. [BOU14]

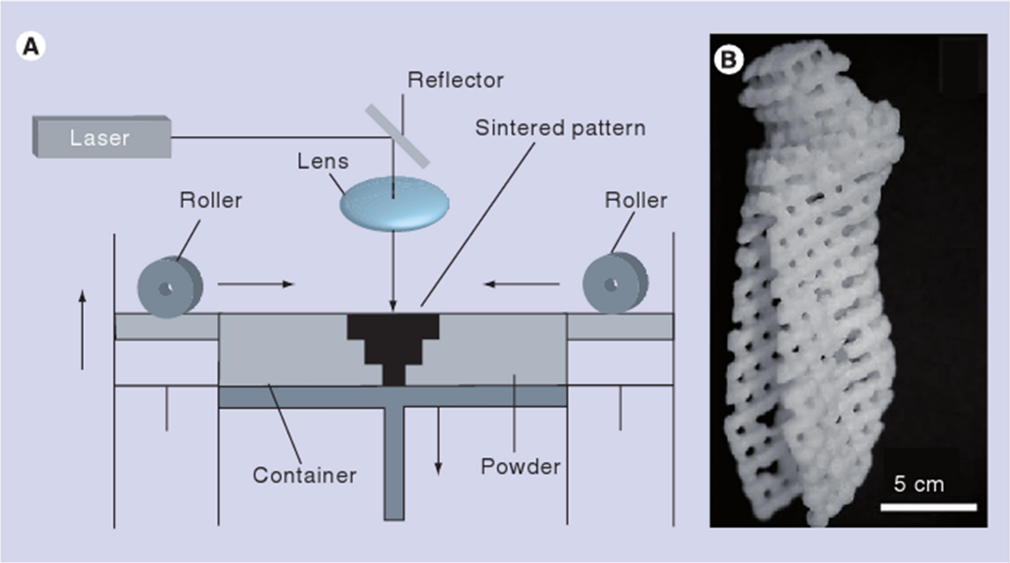


Figure 2.22. Schematic of the laser sintering process [SHA10]

There are multiple advantages of the Laser sintering method:

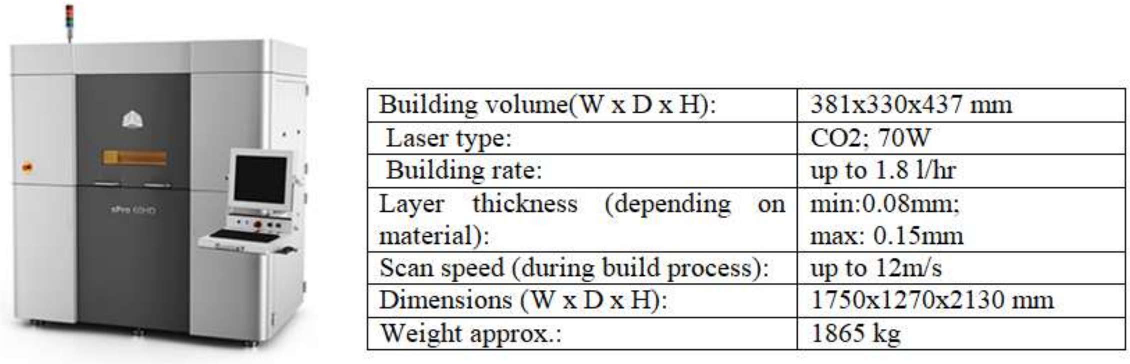
-there are not required supports, (the unfused powder will support the next sintered layer);

- there are not required post-processing methods, like binders that can cause problems with toxicity when the parts are used for medical applications;

- the resolution of the obtained part can be influenced by the beam diameter and the grain size from the powder bed;

- a wide range of materials can be used (from ceramics to metals)

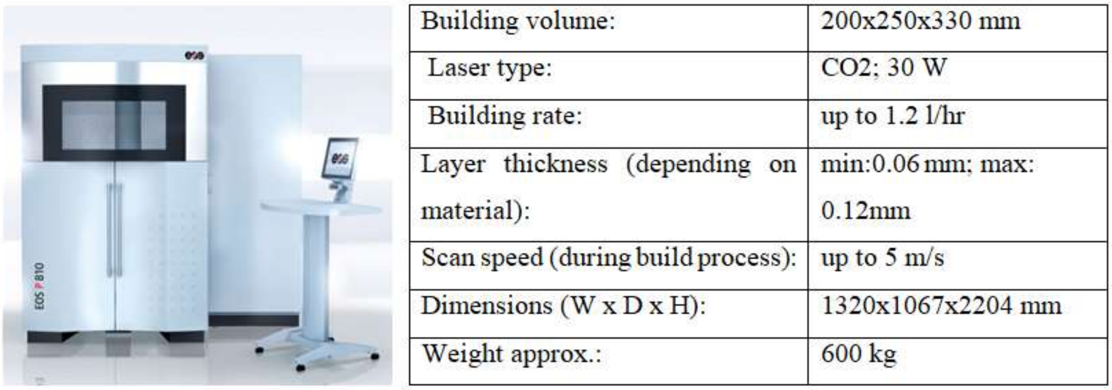
The sPro 60 HD-HS [www03] machine shown in Figure 2.23, produced by 3D Systems, is used in the healthcare and medical field (prosthetics and orthotics). This machine is known for his capability of producing durable and complex parts with a high mechanical properties and chemical resistance creating with a minimum layer thickness of 0.08 mm what can offer very detailed parts, with a maximum building volume of 381x330x437 mm(W x D x H) and sintered with a 70W CO2 laser system as shown in this Figure .



Building volume(W x D x H):	381x330x437 mm
Laser type:	CO2; 70W
Building rate:	up to 1.8 l/hr
Layer thickness (depending on material):	min:0.08mm; max: 0.15mm
Scan speed (during build process):	up to 12m/s
Dimensions (W x D x H):	1750x1270x2130 mm
Weight approx.:	1865 kg

Fig.2.23. The sPro 60 HD-HS machine and its main characteristics; [www18]

The most commonly applied equipment for medical use from EOS is the FORMIGA P110 [www04]. FORMIGA P110 is used for small and medium pieces, has the best detail resolution with a laser power up to 30W, the building rate reaching 1.2liter/hour with a scanning speed up to 5m/s and its' maximum volume capacity is 200x250x300mm presented in Fig.2.24.



Building volume:	200x250x330 mm
Laser type:	CO2; 30 W
Building rate:	up to 1.2 l/hr
Layer thickness (depending on material):	min:0.06 mm; max: 0.12mm
Scan speed (during build process):	up to 5 m/s
Dimensions (W x D x H):	1320x1067x2204 mm
Weight approx.:	600 kg

Fig 2.24. FORMIGA P 110 Velocis and its main characteristics; [www19]

The layer thickness for FORMIGA P 110 goes from 0.06mm up to 0.12mm, for sPro 60 HD-HS this value goes from 0.08 mm up to 0.15mm, so with FORMIGA P 110 more detailed parts can be created because the minimum layer thickness is 0.06mm. sPro 60 HD-HS is quicker because its scanning speed is 2 times bigger than the machine FORMIGA P 110; the scanning speed for sPro 60 HD-HS is 12m/s and for FORMIGA P 110 is 5m/s.

2.4.3. Applications of the SLS technology

In Figure 2.25 it is presented an application from the medical industry under the form of a hand prosthesis. This is similar to the project theme presented in the project in terms of construction. The main advantage in this case comes from the fact that the part from Figure 2.25 has complex geometry that is easy to be produced using SLS printing. The main advantage comes from the fact that the part is produced in one piece, without the need for a supplementary assembly step, as it is needed in a classical manufacturing process. Traditional manufacturing methods can result in poor designs therefore low quality prototypes.

Fig. 2.25. Hand application made by SLS technology using Fuse 1 machine [www20]

Another example could be mentioned the 4 cases of complex spinal disorders that was made from October 2014 to March 2015 in Shenzhen Second Peoples' Hospital in China. The necessary data was collected with a volumetric computerized tomography(CT) and created a 3-dimensional model in “.stl” file by Bio3D software for the 3D printing process as solution for the following disorders (with 1mm layer thickness): congenital scoliosis, atlas neoplasm, atlantoaxial dislocation and atlantoaxial fracture-dislocation.

The created 4 accurate models were used to investigate the case of each patient to plan the operation and collect the necessary equipment and instruments needed for this surgery. For example, at the congenital scoliosis case could not discover obviously the problem, but after creating a 3D model with the CT the following physical model was created after the lifelike dimensions of the patient.(Fig.2.26)

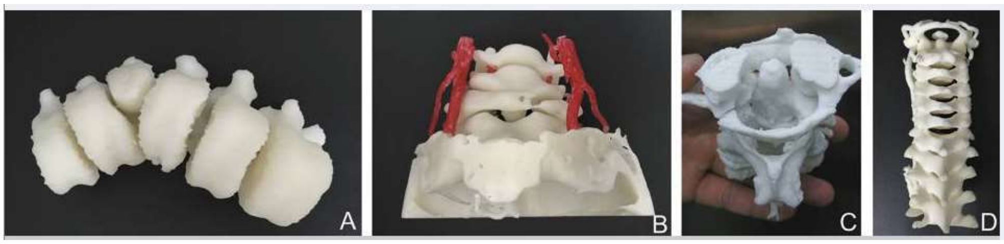


Fig.2.26. The models created for the four cases: a.) Congenital scoliosis L1 hemi-vertebra, b.) Eosinophilic granuloma of C1 (atlas neoplasm) , c.) Fracture dislocation of C1–2 (atlantoaxial dislocation),d.) Dislocation of C1–2 (atlantoaxial fracture-dislocation); [YAN18]

The rapid prototyping process was really helpful because this technology reduced the investigation and operation time by creating a clearer vision about the case and creating a physical model for the surgery. Parts were made of Polyamide material by SLS.

2.5. Selective Laser Melting Technology (SLM)

SLM, also known as direct metal laser sintering (DMLS) or laser powder bed fusion (LPBF), is a rapid prototyping, 3D printing, or additive manufacturing (AM) technique that involves melting and fusing metallic powders together using a high-power-density laser.

2.5.1. Working principle of SLM

Selective laser melting (SLM) is a method of additive manufacturing of details metal, which allows you to produce parts based on 3D computer models designed using CAD programs.

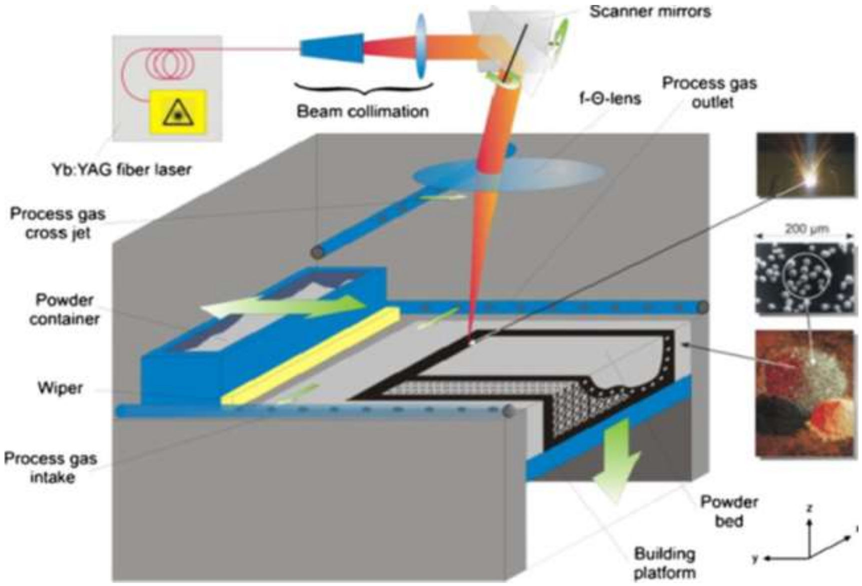


Fig. 2.27. Working principle of SLM [PAC15]

Selective laser melting (SLM) is a manufacturing method that uses a laser to selectively melt layers of loose powder metallic and transforming it into a solid. The generated object is built into a layer by layer from bottom to top. Melting of metal powders or metal alloys is done using high energy laser beams. The laser beam makes a movement consistent with that generated by program path, written in the form of a standardized language for writing commands, that is G Code. There is a powder serving as a building material for the manufactured elements in the litter box. Additionally, the printer has a second cuvette to which the next ones are swept powder layer and in which the detail is produced.

After completing each layer, the bottom of the first litter box is lowered, moving the parts to be method of selective melting metals is carried out under an inert atmosphere, usually nitrogen or argon. Build a printer and the process diagram is illustrated in Figure 2.27 produced downwards, and the bottom of the second the litter box is raised, lifting the powder above the litter level. Then the printer blade moves horizontally, sweeping excess powder from the first litter box to the second litter box. Including At this point, the printer can start producing another layer, and the process repeats itself until to obtain a complete object.

The control software of the SLM system will generate metallic supports which are disposed before taking the package from the platform. Also, the metallic powder is taken along the supports. The main purpose of these supports that are automatically generated by the SLM system is to sustain the part on the manufacturing platform.

These structures help also with the dissipation of heat and residual stresses while holding the part in its place. If designed successfully the supports can fasten up the building process and make it less expensive maintaining at the same time a high quality. In Fig. 2.28 are given different types of supports, the main ones being: block, point and line supports. [JUK14]

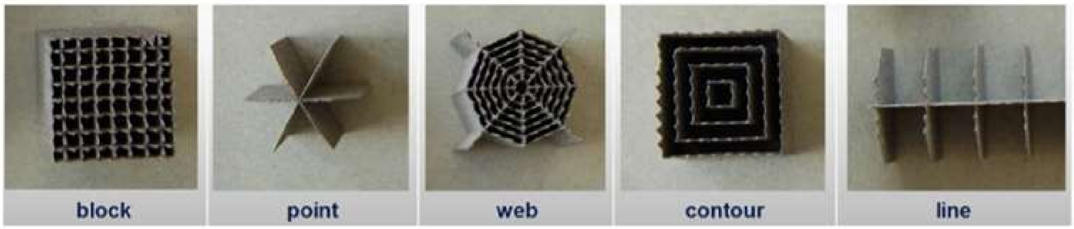


Fig.2.28. Types of support geometries [JUK14]

This project has been funded with support from the European Commission. This publication [communication] reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

While sustaining the overhang surfaces, these supports help to avoid distortion due the residual stresses formed as a result of the thermal cycle. Also, it is important that the contact area between the part and the supports to be minimal in order not to damage the part while removing the supports.

Fig.2.29. Types of support [www21]

The removal procedure can be done manually using tools like ultra-fine needle nose pliers or the supported areas can be milled or polished away.

The materials used in the techniques are highly device dependent as well materials that the manufacturer has prepared for this device. Due to the high complexity process, the manufacturer usually prepares the printing parameters for a given material himself delivers. This gives you the confidence to get good quality prints without having to time-consuming selection of optimal parameters. On the other hand, this solution does not work the possibility of using materials from alternative manufacturers.

In SLM technology, a single powder component is melted and crystallized by CO2 or Nd-YAG laser scanning, compared to the SLS technology it uses metal particles enclosed in a polymer or a combination of different low metal powders and high melting point. Selective melting of the powder allows complete dissolution of all metallic powder particles, generating a compact and stable body Constant. During production, the powder undergoes complex chemical phenomena and physical, such as oxidation, wetting, epitaxial clotting and evaporation.

Additionally, the thermal energy of subsequent laser scans is usually sufficient to re-melt lower layers of details that have already been re-melted.

The advantages of SLM technology include: short design and production cycle, the possibility of producing complex shapes and hollow details, variety implementation materials, creating complex-shaped metal elements in one step, among others. On the other hand, SLM technology also has disadvantages, which include:

- high internal stresses in the detail due to a large gradient temperatures in the vicinity of laser operation; they can cause distortion parts, deterioration of mechanical properties or cracks due to internal stress,
- the need for precise process control resulting from the complexity of the process,
- the risk of the formation of balls on the surface of the detail (the so-called Balling effect), which may result in its inadequate roughness,
- cost of equipment.

The surface quality of details produced by the selective laser melting method has influenced by a large number of factors, including: laser power, scanning speed, orientation of the model's position in relation to the printer's working area, the effect of stepping hatch distance, or type of surface. The laser power determines the severity of the temperature gradient, which is significant influence on surface quality. The scan speed determines the amount of energy consumed during melting, which in turn contributes to a change in the quality of the surface of the part.

The orientation and thickness of the layer are responsible for the so-called stepped effect, shown in Figure 2.30, which is where surfaces sloped to the surface warp the table at an angle other than 90 ° and 0 °. This leads to inaccurate (stepwise) plane mappings. It was also noted that the distance of adjacent beams from each other the laser has a significant influence on the surface roughness. In addition, the surface roughness the upper side also differs significantly from the roughness of the side surfaces. As you can see, the process additive manufacturing with the SLM method is very complicated and difficult to master, for this reason, there are problems with obtaining a detail with appropriate geometry and topography surface. There are many modification techniques to solve existing problems surface of details, including mechanical processes, chemical processes and thermal processes.

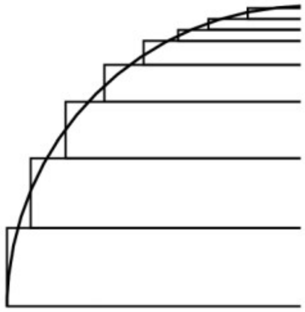


Fig. 2.30. Step effect

The SLM technology allows for the production of metal elements of complex shape in one production cycle. However, precise process control is required due to large temperature fluctuations causing high internal stresses. Big linear energy input density prolongs cooling and solidification. As a result, they arose the pool of molten metal easily absorbs the unmelted powder, leading to a bulge.

The principle of the balling effect is presented in Figure 2.31.

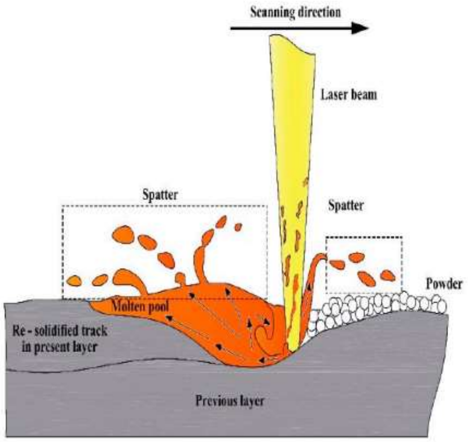


Fig. 2.31. The process of creating the Balling Effect [WAN18]

In the initial layer, this will not cause defects and will not adversely affect the performance printout. This affects the powder coating on the next layer. This problem is made worse with subsequent layers, which may lead to the interruption of the production process.

The splashing of the molten powder occurs throughout the process. It shows several types of spatter that were formed during the interaction laser with powder. Particle splashing is mainly caused by the pressure created by the instant melting of the powder. Another reason there is a rapid heating of the gas inside the powder. It increases under the influence of temperature it scatters the powder particles around the laser beam. But too low energy density means that the powder does not have time to fully melt and only comes for sintering.

Moreover, during the SLM process, the molten laser path tends to be reduced surface energy as a result of the action of surface tension - molten liquid the material takes the shape of small spheres. As a result, there is a good chance of formation balls partially attached to the surface of the work pieces. The number of balls and their size is depends on several factors, including: the material used, the size of the powder particles, thickness layer, laser power, scanning strategy or component orientation in the working chamber.

The occurrence of the balling effect adversely affects the surface topography and makes it difficult to continue development of SLM technology. Other negative aspects of the occurrence can be included the need to use post-processing, which is a complicated process, not to end known, difficult to control and reducing the dimensional accuracy of details. In addition, the pores between the metal balls can reduce strength mechanical parts produced by the SLM method. When a strong phenomenon occurs peening, piled balls tend to collide with the blade of the printer roller; in this way part of the print may be scratched by the blade. This can lead to stop the manufacturing process. This phenomenon is shown in Figure 2.32.

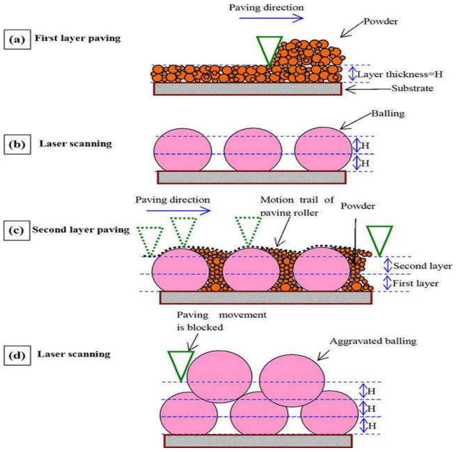


Fig. 2.32. The phenomenon of collision of the blade of the sweeping printer with the surface of the scaffold [YAP15]

The SLM Solutions machine SLM 280 2.0 shown in fig 2.33 is perfect for medium volume part metal production being very robust twin laser melting system which offers a 280x280x365 mm build space. The machine has one twin laser with a maximum power of 1400W that can allow for printing Ni-Based Alloy such as HX that requires up to 1000W laser power. Having a twin laser, the speed of building is 80 % faster than a single one. The optimal parameters for determining TiAl6V4 are min 250 W laser power, 500 mm/s scanning speed, 50µm hatch space, and 30 µm layer thickness.

Technical Specifications

Build Envelope (L x W x H)	280 x 280 x 365 mm³ reduced by substrate plate thickness
3D Optics Configuration Dual Configuration: with switching unit	Single (1x 400 W), Twin (2x 400 W), Single (1x 700 W), Twin (2x 700 W), Dual (1x 700 W and 1x 1000 W) IPG fiber laser
Build Rate (Twin 400 W)	up to 88 cm³/h*
Variable Layer Thickness	20 µm - 75 µm
Min. Feature Size	150 µm
Beam Focus Diameter	80 - 115 µm
Max. Scan Speed	10 m/s
Average Inert Gas Consumption in Process	2,5 l/min (argon)
Average Inert Gas Consumption Purging	70 l /min (argon)
E-Connection / Power Input	400 Volt 3NPE, 63 A, 50/60 Hz, 3,5 - 5,5 kW
Compressed Air Requirement / Consumption	ISO 8573-1:2010 [1:4:1], 50 l/min @ 6 bar
Dimensions (L x W x H)	2600 mm x 1200 mm x 2700 mm
Weight (without / incl. powder)	approx. 1300 kg / approx. 1800 kg

Machine configuration for all types of metal powders / Technical changes reserved

*depending on material and build part geometry

Fig 3.33. SLM 280 machine and its main characteristics [www22]

2.5.2. Applications of the SLM technology

It is known that Additive Manufacturing technologies (AM) are intended for the physical materialization of virtual models with prototype character. It is known and recognized at the same time that every person is a prototype. From these truths it was only a step to look at the extent to which new AM technologies can contribute to improving the quality of life. And so came the idea of using AM technologies in the manufacture of custom stents for each case, first as the geometric shape and then as the structure, properties, and characteristics of the substituted bone.

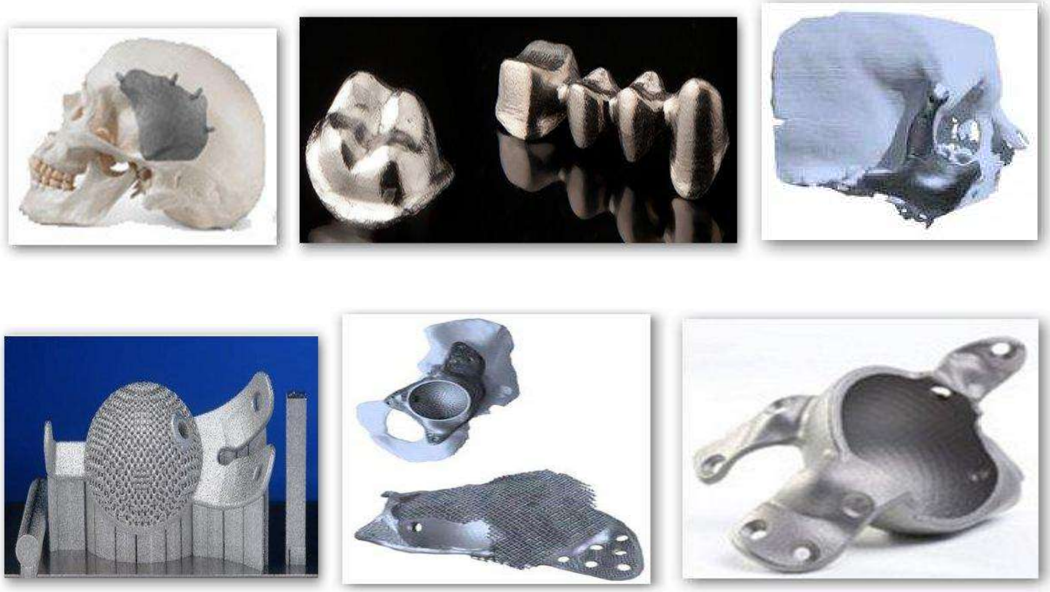


Fig.2.34. Customized medical implants made by selective laser melting SLM method [COS12]

The idea emerged, grew and developed from the experience gained by the team of the National Center for Rapid and Innovative Manufacturing at the Technical University of Cluj-Napoca, Department of Manufacturing Engineering, in the last 25 years in the field of AM technologies and their applications, as well as the endowments of the highest level existing in this center. To these is added the openness and receptivity of the partners from Cluj-Napoca towards such a research with immediate applicability and great interest for a significant number of patients (congenital malformations, serious diseases, accidents, etc.). An idea and a research direction with great social implications that proved its complexity and difficulty as research progressed. The development and solution of such a complex idea required inter and transdisciplinary approaches in areas such as: manufacturing, biomaterials, biocompatibility, physics , chemistry, biology, medicine, reconstructive surgery, etc. In this idea, a strong team with specialists in their fields of expertise was set up in Cluj-Napoca, from the Universities: Technical University, Babeş-Bolyai University, University of Medicine and Pharmacy and Ion Chiricuţă Oncological Institute, which aimed to provide solutions to as many sides of the idea as possible. This is how the BIOMAPIM research project appeared, which, starting from the experience already had in the field and from the achievements and trends worldwide, aims to solve some complex problems regarding the realization of customized medical stents from materials that have a biocompatibility as higher as possible and to reproduce as much as possible the structure and behavior of the substituted area.

In this idea, thousands of experiments were performed by Selective Laser Melting (SLM) of Ti powder alloyed with Al and Nb in order to obtain structures with a certain porosity and physical-mechanical properties as close as possible to those of human bone. These structures were then "surfaced", sol-gel, some of hydroxyapatite (HA), and the like with bioactive glass (SiO2 and TiO2). Hundreds of other experiments followed to determine the optimal values of the working parameters, the adhesion of these new materials to the Ti structures manufactured by SLM. Testing the biocompatibility of new structures and materials, through in vitro evaluations, led to the first results with high scientific value and the orientation of research to a greater extent towards achieving the main objective of the project. In vitro biocompatibility tests have confirmed the significant improvement in the bioactivity of new materials (Ti with HA and Ti with TiO2 and SiO2) through a faster and more massive proliferation of bone cells in their porous structures. In vivo biocompatibility testing of new materials on live animals followed for six months. The implants were well tolerated biologically, producing no adverse foreign body reactions.

In parallel, the technologies for acquisition and processing of tomographic images have been perfected in order to obtain the virtual model of the future stent and the stages of its manufacture have been established in two variants: when the stent will be manufactured by SLS from non-metallic biocompatible materials (polyethyl methacrylate for example) and when the stent will be manufactured by SLM from biocompatible metal powders, figure 2.35.

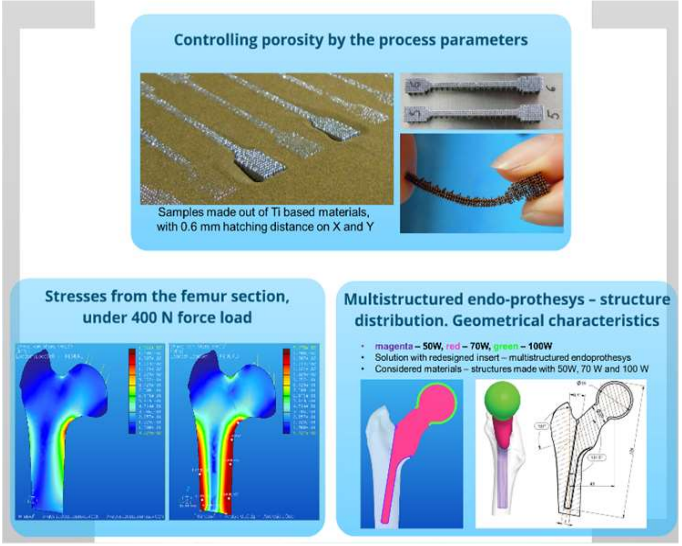
The implementation stage of the results of the first researches meant the participation in the solution of several dozen cases, very diverse, by the Cranio-maxillo-facial surgery Clinic from Cluj-Napoca.

A particular case is presented in figure 2.36. The second stage of implementation consisted in the manufacture by SLM of the first implant from the new materials, for the reconstruction of the zygomatic bone of a patient, for the first time in Romania, figure 2.36.

Fig. 2.35. SLM samples

Fig. 2.36. The first titanium implant made by SLM at TUCN

During the three years of the project, notable results with high scientific and media impact were obtained, results that confirmed several hypotheses and that have already found a practical use in a field as current as quality of life. Participated in national and international conferences, organized several workshops to present the results of the research, published by the team members 24 scientific papers in national and international ISI journals and obtained 4 national patents and one international (registered in the USA and Germany). But, perhaps, the most important is that it has participated with new, innovative solutions in solving complex medical problems of several dozen patients, in a different way than was done so far.



Controlling porosity by the process parameters

Samples made out of Ti based materials, with 0.6 mm hatching distance on X and Y

Stresses from the femur section, under 400 N force load

Multistructured endo-prothesys – structure distribution. Geometrical characteristics

- magenta – 50W, red – 70W, green – 100W
- Solution with redesigned insert – multistructured endoprothesys
- Considered materials – structures made with 50W, 70 W and 100 W

Fig. 2.37. Samples and hip implant prostheses made by SLM at TUCN

Working in such a team has not only produced results, but also defined new ideas and research directions in such a complex field.

The inter and transdisciplinary team set up and consolidated within this project aims to continue their research together, focusing on:

- production of multi-structural endo-prostheses, predefined in volume and with controlled physical-mechanical properties (fig.2.37);
- improving the properties and characterization of the active surfaces of multi-structured porous stents;
- testing in vitro biocompatibility and tissue regeneration potential;
- in vivo biocompatibility testing of new materials for the repair of induced bone defects;

- testing the antitumor effect of surfaces loaded with antitumor drugs in a dying model of Ewing sarcoma

In Fig. 2.38 and 2.39 are presented two other examples of implants that were made by SLM as result of research that has been performed within the projects that were mentioned in the preamble being made within the National Center for Rapid and Innovative Manufacturing at the Technical University of Cluj-Napoca, Department of Manufacturing Engineering, in cooperation with Babeş-Bolyai University, University of Medicine and Pharmacy and Ion Chiricuţă Oncological Institute of Cluj-Napoca.

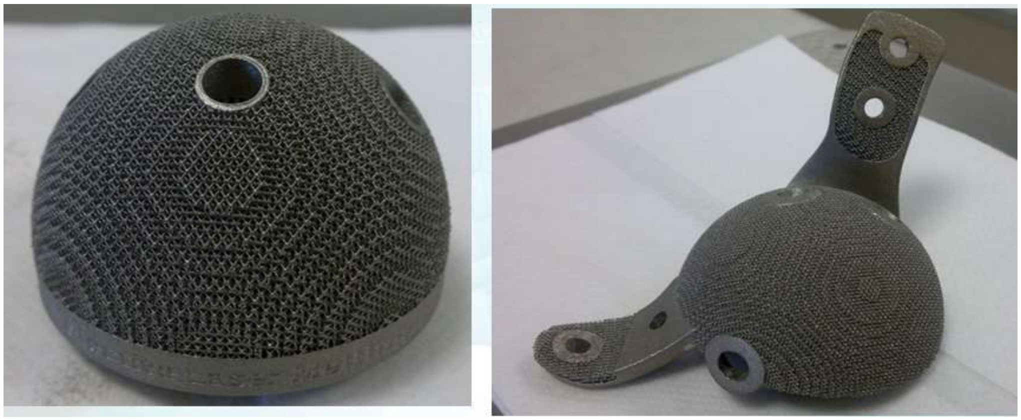


Fig. 2.38. Hip implant made by SLM

Fig. 2.39. Surgical operation performed using implants made by SLM at TUCN

This project has been funded with support from the European Commission. This publication [communication] reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

2.6. Stereolithography technology SLA / Polyjet / DLP

2.6.1. Introduction. Presentation of the Stereolithography (SLA) technology

SLA / Polyjet / DLP are 3D printing technologies that are based on the photopolymerization of a resin. These 3D printing technologies become popular for its ability to produce high-accuracy, isotropic, and watertight prototypes and parts in a range of advanced materials with fine features and smooth surface finish. It is used in wide range of industries such as manufacturing, dentistry, healthcare, education, entertainment, jewelry, audiology, and more.

The fundament of stereolithography is the solidification reaction of liquid resin. It is an exothermic polymerization process characterized by chemical cross-linking reactions. The reaction is initiated by supplying the energy of UV light and there are two transitions during the solidification reaction process: gelation and vitrification. Gelation is a liquid-to-rubber transition which is reflected in increase in viscosity. During gelation, in the resin coexist gel phase and sol phase at the same time. Vitrification, on the other hand, is a gradual, thermo-reversible process that leads to the transition from liquid or rubber resin to solid resin.

Modern approach of stereolithography started in early 1970s when Japanese researcher Hideo Komada used UV light for solidification of photosensitive polymers. The term “stereolithography” (Greek: stereo-solid and English: lithography – special method of printing) was given in 1984 by Chuck Hull in his patent where he described stereolithography as method of 3D printing by successively printing thin layers of an object using ultraviolet light for solidification. After Hull proposed and lunch stereolithography printers on the market, there were four generations (Figure 1) of technological innovation [HUA20].

1. Laser Scanning Stereolithography – printing a 3D object by scanning with a focused laser beam over resin surface for solidification.
2. Projection Stereolithography – printing each layer of an object simultaneously with a single exposure by projecting mask patterns on the resign surface.
3. Continuous Stereolithography – creating continuous process, first exposing resign to UV light, second moving/shifting and third re-positioning.
4. Volumetrical Stereolithography – formation of 3D object in a single operation.

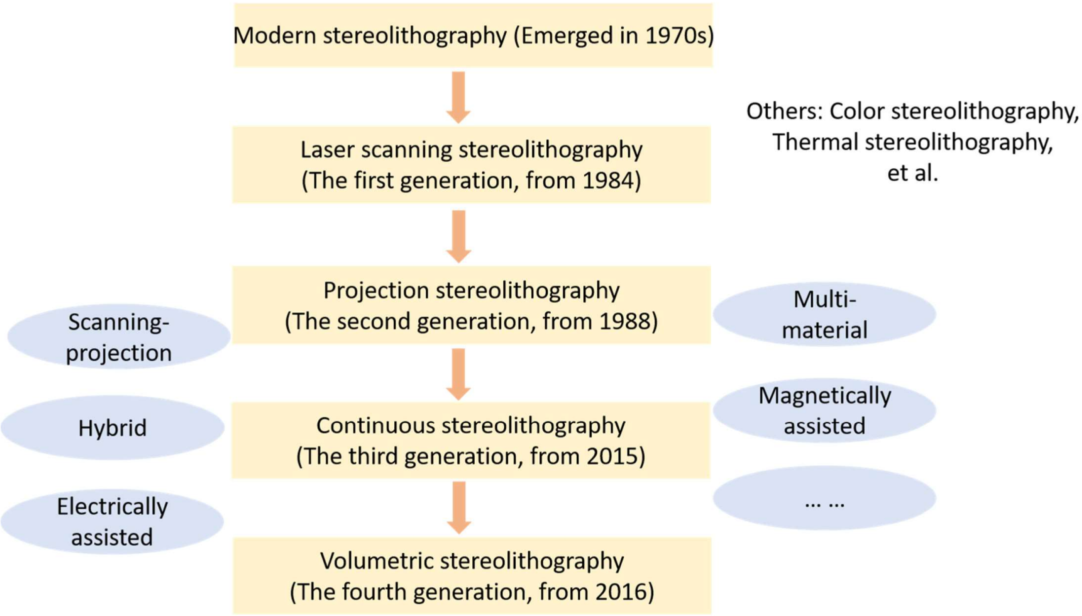


Fig.2.40. Overview of Stereolithography technology [HUA20]

Photopolymers or light-activated resin is a polymer that changes properties when they are exposed to light (UV or visible region of the electromagnetic spectrum). These materials are degrading over the time especially when they are inappropriately stored regarding temperature and light. Also, it is hazardous to work with them and for normal operations with photopolymers is advice to have appropriate conditions.

2.6.2. Working Principle of the SLA technology

There are various 3D printers on the market that are using resin photopolymerization as basic physical principle for printing such as SLA, DPL, LCD etc. where is difference only is light source. Also, Polyjet is using resin photopolymerization for solidification although it is material jetting 3D printing process.

Stereolithography (SLA) is also known as SL, optical fabrication, photo-solidification, or resin printing. During the SLA manufacturing process, a concentrated beam of UV light or a laser is focused onto the surface of liquid photopolymer. The UV light is focused and it create each layer of desired 3D object, fig.2.41.

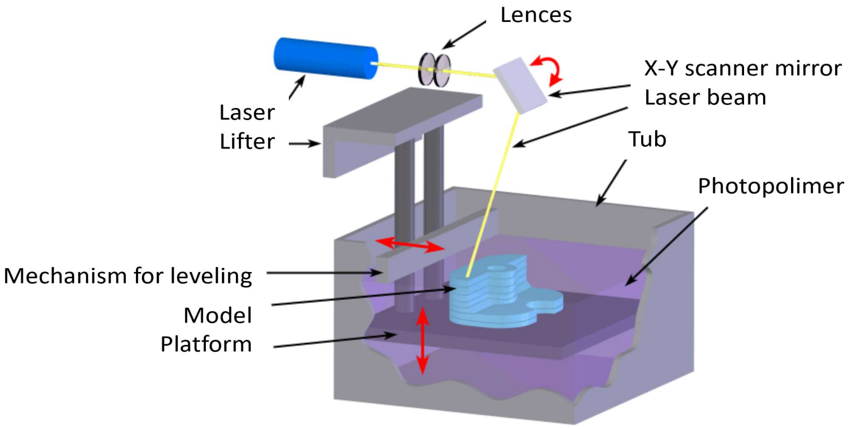


Fig. 2.41. SLA/DLP 3D printer working principle [www23]

Figure 2.42 represent two basic architectures of 3D printers like SLA, DLP and LCD where light source can be on the top or on the bottom. On the Bottom-up architecture light source is under the vat, platform is in beginning in overlay with resin in the vat and it is moving layer by layer up and it emerge from resin. In Top-Down architecture, light source in over the vat, platform is immersed in vat all the time and it is moving down layer by layer. During the printing process platform cannot be seen and on the end of the process it emerge from vat.

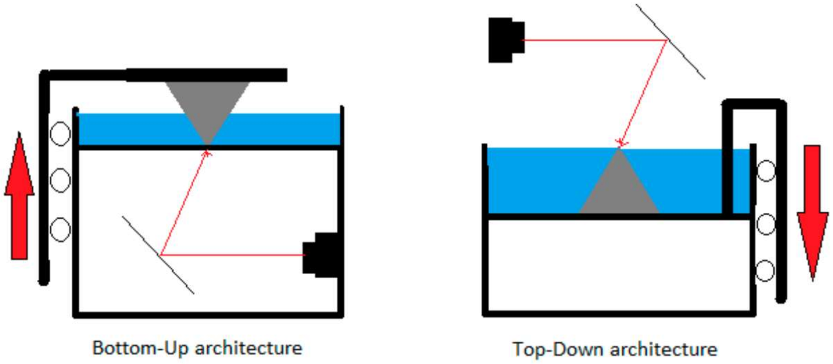


Fig. 2.42. SLA printer architecture [MAO18]

Digital Light Processing (DLP) 3D printing use a digital projector screen to flash a single image on each layer across the entire platform. Because the projector is a digital screen, the image of each layer is composed of square pixels, resulting in a layer formed from small rectangular bricks called voxels. DLP can achieve faster print times for some parts, as each entire layer is exposed all at once, rather than drawn out with a laser.

This project has been funded with support from the European Commission. This publication [communication] reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

PolyJet 3D printing technology was first patented by the Objet company, now a Stratasys brand. The photopolymer materials are jetted in ultra-thin layers (normally between 16 and 30 µm) onto a build tray in a similar fashion compared to inkjet document printing. Each photopolymer layer is cured by UV light immediately after being jetted. The repetition of jetting and solidification steps, layer after layer produces fully cured models that can be handled and used immediately.

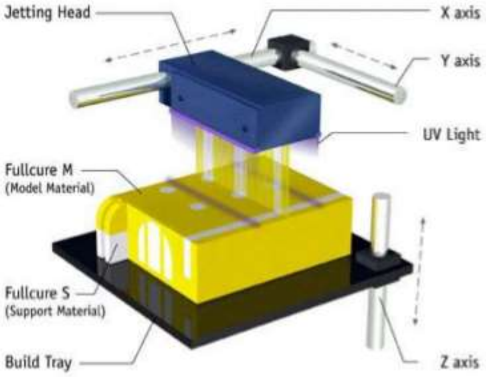
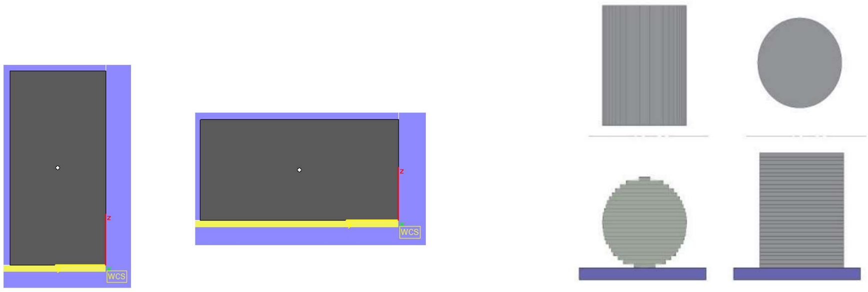


Fig. 2.43. Polyjet 3D printing principle [www23]

Fabrication process

The fabrication process of stereolithography (Figure 2.44) starts like all standard 3D printing processes from STL file. 3D STL file is cut to 2D slices which form physical model with some of sliced software. Some of slicer software for STL are CHITUBOX Free, Envision One Software, PreForm, Z-SUITE, PrusaSlicer, Formware, B9Creator etc. STL prints must have support structure for all the angled or in space surfaces to prevent full or partial collapse of printed parts.



a) b)

Fig. 2.44. Positioning of part for printing

Important parameter of printed parts are printing time, strength, roughness and support structure. All these parameters are primarily depending on the way how the part is positioned on the printing platform and how printing. 3D printing time depends also on the speeds of light source, but this is defined by producer of printer and often cannot be influenced. Users can influence 3D printing by the way how they made position of the part since the parts can be position horizontally or vertically (Figure 2.44.a) and all producers are advising that parts need to have some angle since the parts are stronger. Also, positioning of a part is influencing roughness (Figure 2.44.b). Here is important question of support structure that need to be integrated on the part since the surface where support structure is foreseen is going to be postprocessed and cleaned which means that these surfaces are going to have lower quality.

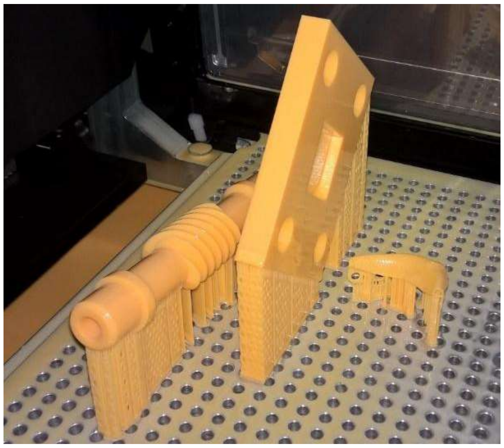


Fig. 2.45. STL parts on platform after printing process [www24]

The standard printing process of 3D printing for Top-Down architecture is shown on Figure 2.46. Laser is moving from one side to another that which is x-y direction of printing. During this process laser is solidifying one layer according to the sliced 2D crossed section. When the layer is finished in next step platform goes for the size of a layer down which is z-direction and then starts again move of laser from one side to another for solidification of the next layer.

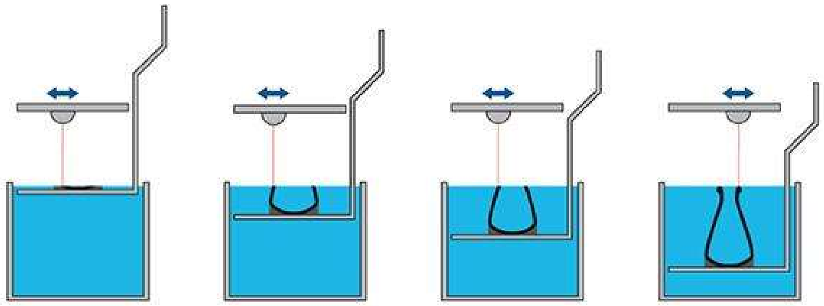


Fig. 2.46. SLA printing process with Top-Down architecture [www24]

One specific of SLA printer is creation of hollow parts. Since the printing of full filled parts is expensive and, in many cases, needless option of hollow parts advice is to use hollow parts and all slicer software are giving this option. For hollow parts is important to foreseen technical holes that are important in these cases so that resin can go out of part and not to be captured into the hollow part. Some producers of SLA printers are advising that diameters of technological holes should be at least 4mm.

Stereolithography has possibility to fabricate parts with biodegradable material and open topics like tissue engineering. Some of polymers for stereolithography of biodegradable structures are those who contain poly(propylene fumarate), trimethylene carbonate, poly(ε-caprolactone) and poly(D,L-lactide).[SKO20]

2.6.3. Medical application of SLA

High precision and efficiency of DLP and STL printers make them very suitable for dental industry. They found their place in this industry for making templates for guided implant surgery, education models, custom impression trays, production of occlusal splints, printing single tooth crowns etc.

Education and training models

Realistic patient models for education are interesting for dental industry since this has to be standard in their training. Figure 8 show realistic model fixes on standard phantom heads. In order to save material they can be hollow as well as they can possess reinforcing grid.

Fig.2.47. Realistic model for training models [SCH19]

Precision-fit occlusal splints can be produced by STL printing due to overall production accuracy, the quality of material. Here is also necessary to show that materials have good properties regarding long-term stability and biocompatibility.

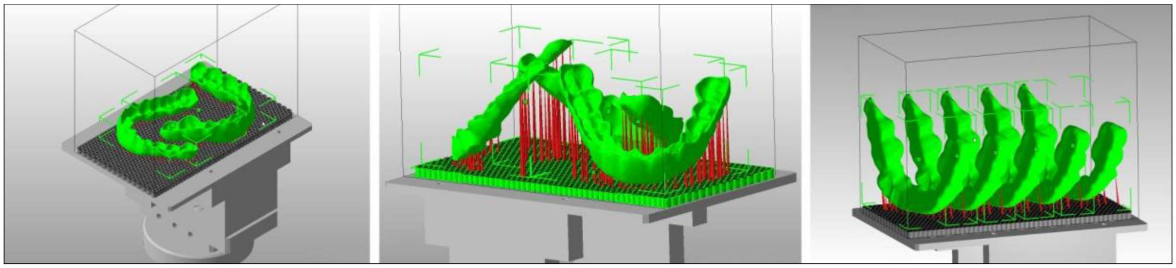


Fig.2.48. Orientation of occlusal sprints at platform [SCH21]

Using intraoral scanners allow creation of guides for implant surgery. Every template has to be unique and custom made based on radiology DICOM data. After processing DICOM data and creation of STL data, templates can be very quickly produced at low costs.

Fig. 2.49. Surgical guide [www25]

Prosthetics fitted on a stereolithography printed model; note the precision of the restorations produced using computer aided design/computer aided manufacturing technology (Fig. 2.50).

Fig. 2.50. Stereolithography printed model for fitting prosthetics [PAT17]

German company Bego offers since 2020 3D printing of permanent single-tooth restorations, Figure 2.51. For this purpose, they develop ceramically reinforced hybrid material and it is produced with low-cost, high resolution DLP 3D printer. [www 26]

Fig.2.51. Single tooth crowns [SCH21]

STL 3D printing made significant improvement also in the orthopedic surgery. Use of 3D printing made development of prosthetics and joint replacements. Reconstructive surgery is suitable for use of stereolitography and for creating the possible templated from standard imaging methods like MRI and CT scans.

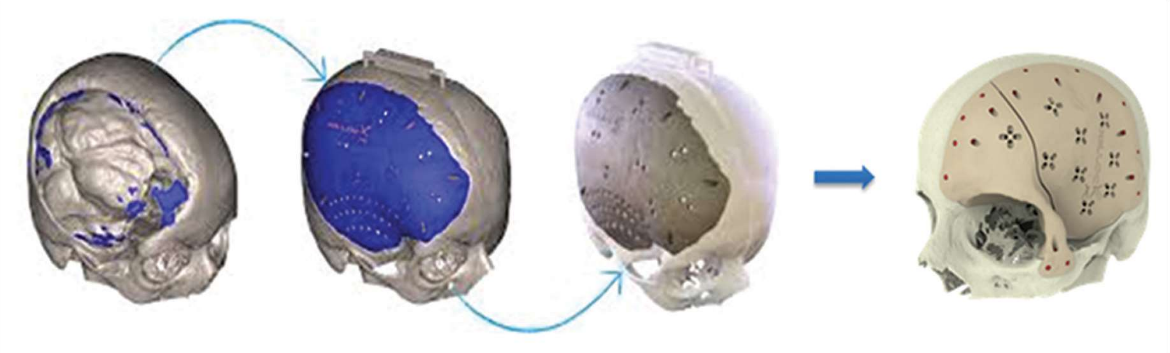


Fig.2.52. Example of 3D printed skull from magnetic resonance imaging to 3D printed model [KAZ18]

STL fabrication of trapezoid condyle plate is used also for increasing the medical operations in the cases where personalized anatomically adjusted plate is needed for fixation of human mandible condyle process. Personalized trapezoid condyle plate serves to speed-up operation procedure in the critical phase for taking exact shape of broken mandible.

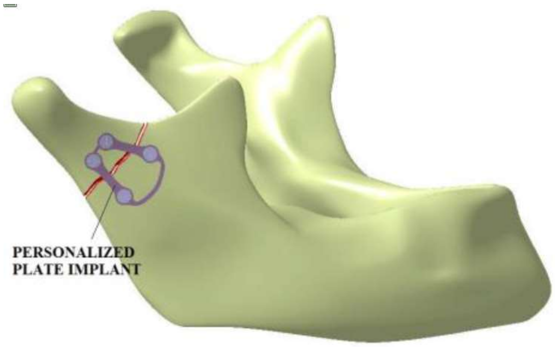


Fig.2.53. Trapezoid condyle plate for personalized plate implant [MIT17]

Fig.2.54. Hearing aids [www27]

SLA 3D printing technology imposed as very suitable in the market of hearing aids. Majority of hearing aids world production are produced now with SLA technology. Excellent customization and smooth surface allow high level of details and comfort. For this purpose, are develop special materials.

3D printing in tissue engineering open possibility to create tissue that can be implant in animal and human body. Researchers start to work on the organs like: kidney and urinary system, pancreas, liver, cardiovascular system, pulmonary system, trachea etc.

Among the most advanced applications of 3DP is the area of bioprinting of tubular structures, from large vessel grafts to the trachea. 3D printing has been used to create tracheal scaffolds that are suitable for human implantation. In the field of vascular surgery, and especially endovascular large-vessel interventions, 3DP models have provided an important platform for preoperative planning in complex/challenging cases.

Great step in treating cardiovascular are implantable 3D printed cardiac valves, Figure 2.55. Aortic valves were successfully printed using polyethylene glycol-diacrylate hydrogels supplemented with alginate.

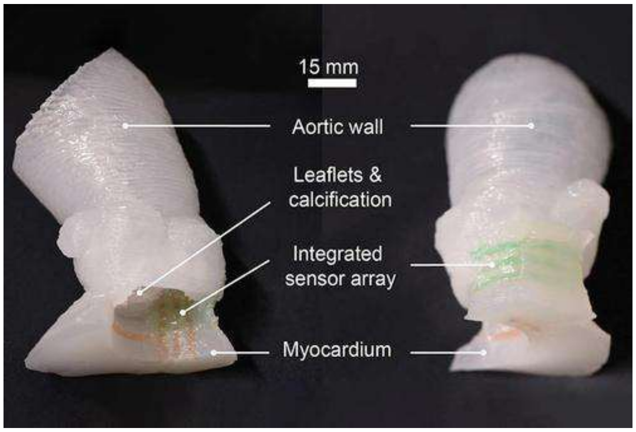


Fig.2.55. 3D printed cardiac valves [www28]

Fig.2.56. 3D printed human lung [www29]

3. Rapid Tooling methods

3.1. Introduction about the use and opportunity of using Rapid Tooling methods for medical applications

Rapid tooling is a process that enables creation of tools or molds in a short amount of time. It is generally faster and more streamlined than conventional tooling. There are two different types of rapid tooling direct and indirect tooling. Direct tooling is a manufacturing process in which single mold or tool is made. In indirect tooling, master pattern is produced, which enables creation of different types of molds or tools. Each of these technologies, can be represent by a sequence of operations, and they are presented in Table 3.1, for both methods.

Table 3.1. Different types of rapid tooling

Direct Tooling	**Indirect Tooling**
1. Creation of CAD model for the tool or mold 2. Production of the tool by using additive technologies or CNC high speed machining. 3. Application of the tool for the creation of the prototypes. Usually, not large number, but it can be if adequate materials are used.	1. Create a master pattern CAD model 2. Production of the master pattern (mold or tool), usually very durable 3. Create mote tools or molds based on the master pattern. Soft (less robust and weaker material) and hard (stronger material, very robust) tools can be made 4. Master patter can be used for producing many various tools and molds, therefore, more prototypes can be created.

In General, direct tooling can be used when we need short-run production, or we want to create some design ideas because it creates one kind of mold or tool for creation of a product, so to use it for prototyping in might be cost-ineffective. For prototyping, it is better to use indirect tooling, because it enables application of different types of materials and design, based on the created master pattern for the final design of the product (silicone rubber tooling, epoxy-based composite tooling). Because, direct tooling is a very well-known process, more information will be provided for indirect tooling, and for three different material-based approaches:

Silicone rubber tooling –helps obtaining small and medium parts with fine details in a quick and not expensive way, from different materials. One disadvantage of the method can be the difference of properties between the urethane and thermoplastic materials that are used in the manufacturing process. Due to the flexibility of silicone, the negative draft (undercuts) can be obtained easily.

Epoxy-based composite tooling is using an AM manufactured master pattern. The pattern is embedded in the parting line block to create the parting line of the mold. In order to ensure the resistance of the epoxy resin during the injection molding process, metal inserts are used. For the first part of the tool, epoxy is poured on the pattern and parting line block combination. After the epoxy is polymerized, turn the component upside down and remove the parting line, leaving the pattern embedded on the first side of the tool. The second side of the tool is then cast against the first. Tools are frequently created as inserts to be mounted in a mold base.

Spray metal tooling is very much like epoxy-based composite tooling, the only difference is that a thin layer of metal deposited using a spray gun to create the surface of the mold. The metal used is often a zinc-based alloy, but it can be sprayed other metals, including steel. The metal surface is then backed with epoxy or a low-melt alloy. The backfill material can help the cooling rate of the tool. One advantage for spray metal tooling is that is very good for large parts also because the metal surface of the mold decrease the injection cycle. Oder advantage is that during the mold-making process are not introduce shrink.

The complex shapes of the mold and the limited life are some disadvantages because increasing the production time and also the costs. The spray metal tooling is suitable for applications with parts of significant size and low-to-medium complexity.

3.2. Example of using direct tooling method (Metal Spraying method) in medicine

The developed method have three pre-processes which are mandatory in order to generate an exactly geometrical model (surface, solid, parametric model) of the specific human bone, as presented in Fig. 3.1.

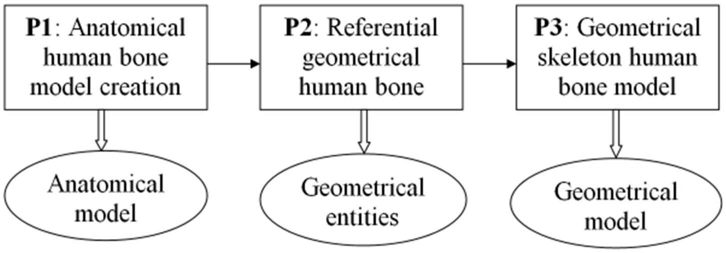


Fig. 3.1. Processes for the creation of bone model

This method is based on anatomical properties and also on human bone morphology in order to create the exactly human bone geometrical model. In the preparatory processes for bone models is create a descriptive model with a set of anatomical landmarks which are in medicine, in detail defined. The first steps are the creation of the anatomical bone with well-defined areas of human bone and find the useful information about basic bone morphology (P1). The creation of the basic geometry model is the next step and the following operations are done: Using Computer Tomography (CT), the human body or dry samples are scanned (in this case femur); Preprocessing of raw data (scans) which are transformed into STL format; After that, the scanned model from STL format is transformed into the 3D model using a CAD application (for example CATIA); Adjusting the cloud of points; Tessellation and Healing the tessellated model. The polygonal geometrical bone model is created in the final of the preparatory processing processes. These processes described upper are so called preparatory processes which are very important procedures of referential geometry defining - RGEs (plains, lines, axis, points, and so) which is well defined on polygonal human bone model with totally compliance of its anatomical and morphological features. In order to create geometrical entities after defining RGEs (P2), will follows the examination of polygonal bone model. The geometrical entities will serve as base for creating the geometric model(s). In order to follow the bone geometry and topology in the best way possible and all in accordance with anatomical bone model (P3) the geometrical entities are mainly spline curves (B-spline). In the final the solid model is created, and ready for the further application, which is in this case **direct tooling** for the creation of mold for the presentation models.

An injection mold can be very quickly created using metal spraying on the RP model. With a hand-held gun operated manually the metal spray shell is fixed on the RP model surface. The mold can be used for a limited number of prototype parts. An electric arc is introduced between two wires, which melts the wires into tiny droplets [CHU03]. Compressed air blows out the droplets in small layers of approximately 0.5 mm of metal.

The master pattern produced by any RP process is mounted onto a base and bolster, which are then layered with a release agent. A coating of metal particles using the arc spray is then applied to the master pattern to produce the female form cavity of the desired tool. A reinforcement backing is selected and applied to the shell in function of the type of tooling application. This procedure of producing soft tooling has advantages regarding the costs and lead-time. A typical metal spray process for creating an injection mold is shown in Figure 3.2.

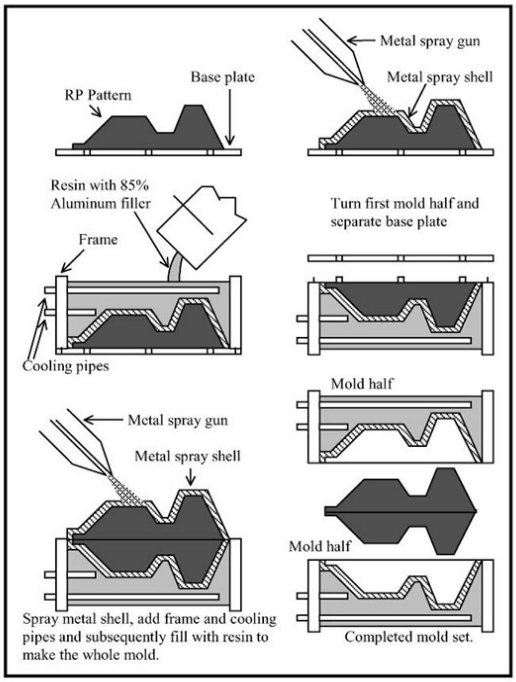


Fig.3.2. A metal arc spray systems [CHU03]

First step is to define a human femur bone model, by applying the defined procedure and using DICOM images as input, Fig 3.3.

Fig.3.3. Femur Surface model created in CATIA v5 R21

Next step is to create mold CAD model, also in CATIA, by using adequate technical features. The CATIA mold is presented in Fig 3.4.

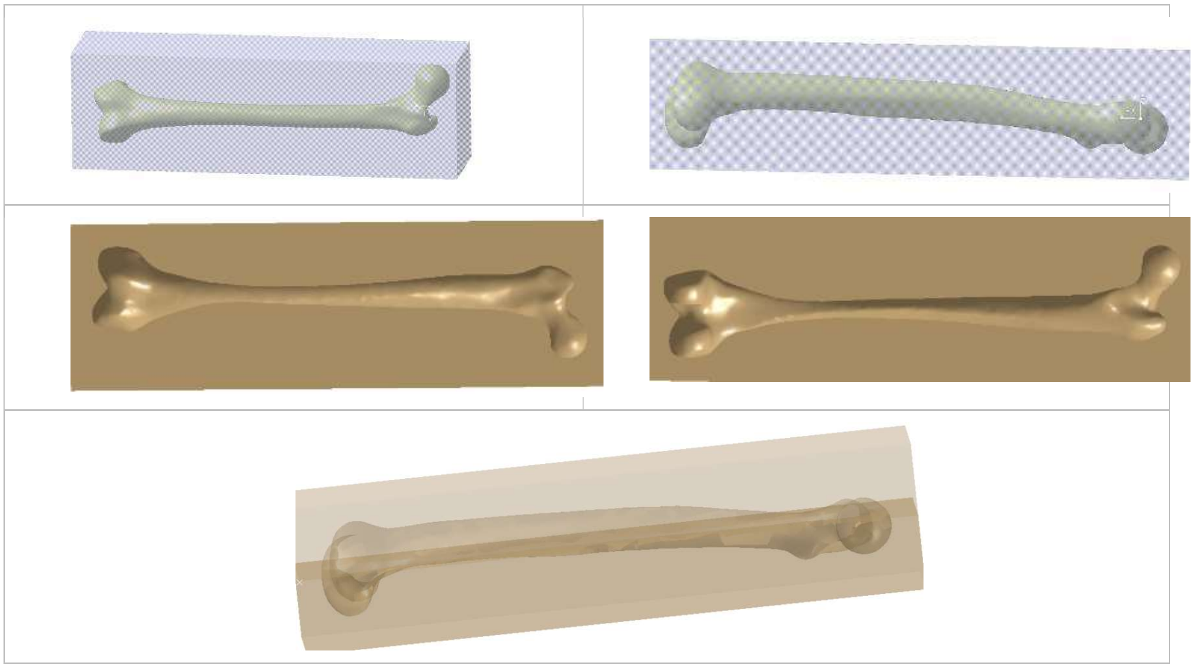


Fig 3.4. Femur mold creation process

The mold model were sent to the company (D-Company, Babusnica, Serbia) for manufacturing and mold models were adjusted, produced, and presented in Fig 3.5.

Fig. 3.5. Mold and Femur presentation models

3.3. Example of using Vacuum Casting method in medicine

The process of vacuum casting is characterized by the fact that the process is using vacuum while making different object, in this case while making the mould and the casting parts. This process is made using a master model, which characterized an soft indirect tooling process, soft because the material, the silicon rubber material, does not support casting a large number of products to be made. The manufacturing of functional plastic, metal and ceramic components, using the vacuum casting procedure with silicone rubber mold has been the most flexible used because of the flexibility of the process. The procedure has the following advantages:

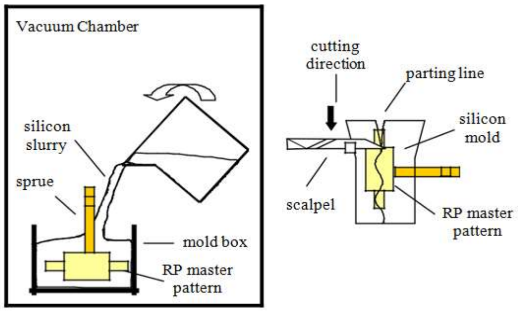
- Extremely high resolution of master model details can be easily copied to the silicon cavity mold.
- Gross reduction of backdraft problems (i.e., die lock, or the inability to release the part from the mold cavity because some of the geometry is not within the same draw direction as for the rest of the part).

The Renishaw PLC is a producer of equipment for the manufacturing industry, and equipment for the health and control-measurement sectors. based in United Kingdom, Wotton-under-Edge, Gloucestershire. The company was founded in 1973 by David McMurtry and John Deer. The company has assembly lines in Dublin (Ireland) and Pune (India), as well has two research centers, one in Wotton-under-Edge, Edinburgh, UK, and the other in Ljubljana, (Slovenia). [www30]. The Renishaw customer base includes top manufacturing innovators focused on industrial development such as: SuperAlloy Industrial Company Ltd. (Taiwan), Silfex Inc. (USA); institute: Beijing Institute of Technology (China); and healthcare:

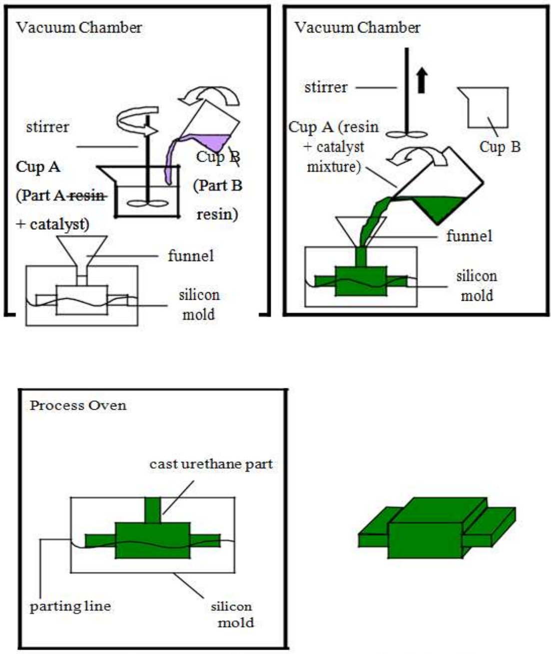
Charing Cross Hospital, London (UK). The company is one of the leading manufacturers of vacuum casting equipment with three such equipment items that it produces: 5/01 ULC, 5/01 PLC, 5/04 PLC, the main difference between all these equipment items is the size of the equipment and implicitly the size of the vacuum chamber, 5/01 ULC being the smallest and 5/04 PLC the largest, the company also produces 3D printing equipment such as (AM 400, RenAM 500Q, RenAM 500M, EVO Project). The materials used by the company are: Metal (SS316L-0407, In625-0402, AlSiMg-0403, CoCr-0404, Ti6Al4V) used for metal 3D printing [www31], and for vacuum casting is used Polyurethane (SG95, 6130, 8020-2, 8045, 8051, 8263, 8891, 9012) [www32].

The SLM Solutions Group is a company with the headquarters in Lubeck, Germany. The company deals with construction of SLM equipment and provides solutions with Investment Casting processes. They are also known for building Vacuum Casting equipment (VCM 04, VCM 06, (VCM04 being the smallest and VCM 06 the largest). The most important customers of the SLM Group company are: Abb (Zurich, Switzerland), Arno Werkruge (Karlsbader, Germany), Kraiburg Austria (Geretsberg, Austria), Hirschvogel Solution (Bayern, Germany), Thaletec (Thale, Germany), Werkzeug-Und Machinenbau Gbmh (Thuringen, Germany). The materials that SLM Solutions Group uses for Vacuum Casting, are: Resins (8060HT-1, 8060HT-2, 8060HT-3, 8060HT-4, ZT85, ZT86, 9011), Silicon Rubbers (VTV 750, VTV 800, VTV 850, VTX 950) ,Nylon PA6 materials (VTX 5900, VTN 4500, PA 3000, PA2000, PA1001, PA700) and Polyurethane (SG95, 6130, 8020-2, 8045, 8051, 8263, 8891, 9012), the main field in which these materials are used is the industrial field. [www33]

The models obtained by RP can be used as master models to create these silicon rubber molds. In Fig.3.6 the mold creating process is presented. The master model, which is attached with a system of sprue, gating, and air vents, is suspended in a container. Silicon rubber mixture is poured into the container until the master pattern is completely covered. The silicon is baked at 70°C for three hours until solidification, and after that a parting line is cut. The master model is removed from the silicon mold resulting the tool cavity. The halves of the mold are then taped together firmly. Materials, such as polyurethane or epoxy resin, can be poured into the silicon tool cavity. The casting process takes place under vacuum to avoid asperities caused by entrapped air. The curing process of the cast polymer part can take place at room temperature (20℃) for around 24H or baked around 4H at 70℃ depending on the material. A silicon rubber mold can be used to produce up to 20 polyurethane parts because after that it begins to break apart [www33].



(a) Producing the silicon mold (b) Removing the RP master pattern



Cast urethane part cured in a baking oven

The final rapid tooled urethane part

Fig. 3.6. Vacuum casting with silicon molding [CHU03]

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Dimensions without accessories (H × W × D)	1930 mm × 1510 mm × 900 mm (add 380 mm (15 in) to height, for nylon module) (76 in × 60 in × 36 in)
Maximum recommended mould size (H × W × D)	550 mm × 800 mm × 600 mm (21.6 in × 31.5 in × 23.6 in)
Casting capacity	2 L, 5.5 L or 11 L with twin robot (122 cu/in, 335.6 cu/in or 671.2 cu/in with twin robot)
Power supply	3 phase 400 V NPE, 50 Hz, 3.5 kW – other power supply configurations are available
Pump capacity	65 m³/hr (2295.5 cu/ft)
Ultimate vacuum	0.5 mbar (7.25 psi)
Gross machine weight	1150 kg (2535 lb)
Features	PLC control and automation – to ensure consistent casting Vario-Vac™ differential pressure system for casting high viscosity resins
Options	Nylon Plus – for casting high performance glass or fibre filled PA6 nylon Heated cup – suitable for casting high quality wax masters and low melt alloy Twin robot – for increased casting capacity
Ancillaries	Extension chamber – for projects larger than the capacity of the standard system
Support	Maintenance packages Training programmes – tailored to suit your requirements Consumables – including PU resins and silicone rubbers

Fig 3.7. Renishaw 5/04 PLC vacuum casting system equipment and it's characteristics. [www34]

In Fig 3.7 is presented a Vacuum Casting 5/04 PLC equipment produced by Renishaw company which use Polyurethane (6130) material to produce consumer goods. As can be seen an example of a piece of polyurethane intended for general consumption made with the help of equipment 5/04 PLC is shown in Fig 3.8, but industrial components can also be produced. The dimension of housing is 1930mm x 1510mm X 900mm and the maximum mold size 550mm x 800mm x600mm (which makes it suitable because the mold made for the part presented in Fig 1.1 has a size of 260x110x100 mm), it has a pouring capacity of up to 5.5 liters or 11 liters with twin robot. The equipment has a pump capacity of 65m^3 / h (which leads to a faster filling of the mold because the volume of the cavity inside the mold made for the part in Fig 1.1 has a volume of 27034 mm ^ 3), and an ultimate vacuum of 0.5 mbar. The 5/04 PLC equipment also has a feature called Vario Vac that offers it a differential pressure system for casting high viscosity resins.[www34]

In Fig 3.8 is presented an example of VCM 04 equipment made by SLM Solutions Group, the only vacuum casting equipment, manufactured by SLM Solutions Group, compatible with silicone-rubber/polyurethane material, the equipment being intended for the production of parts for mass consumption, but also for industrial components. The equipment have a dimension of the housing of 1930x1510x900 mm, which means that it has the capacity to support molds of a maximum size of 750x900x750 mm.

Anlagenparameter System Parameters	VCM 04/Nylon
Gießgewicht Casting Capacity	100 g - 5,0 kg
Max. Formenmaße Max. mould dimensions	H 750 x W 900 x D 750 mm
Außenmaße External dimensions	H 1930 x W 1510 x D 900 mm
Form - Lift, Tragkraft Mould - lift	150 kg
Elektrischer Anschlusswert Power supply	400 V, 50 Hz, 3,5 KW, 3 Phase
Hochleistungs-Vakuumpumpe High capacity vacuum pump	65 m^3/h
Vakuumdruck Vacuum level	0,5 mbar
Geräuschpegel Noise level	65 dBA
Gesamtgewicht Total weight	1300 kg
Farbe Colour	RAL 7035, lichtgrau RAL 7035, light grey

Fig 3.8. SLM Solutions VCM 04 vacuum casting system equipment and it's characteristics [www35]

The materials used for this equipment are: Casting Resins, Nylon PA 6, Silicon Rubbers (VTV 750, VTV 800, VTV 850, VTX 950), and Polyurethane (SG95, 6130, 8020-2, 8045, 8051, 8263, 8891, 9012).[REN21] The equipment has a casting capacity from 100g to 5 Kg a vacuum pump capacity of 65 m^3/h and an ultimate vacuum of 05 mbar. The equipment can also support molds weighing up to 150 kg, The equipment is equipped with a 3-phase motor, 400 V, 3.5 KW, 50 Hz.

Having one similar equipment available at the Technical University of Cluj-Napoca, the following research has been performed for realizing an implant at the skull level as shown in Fig.3.9.

In this case, the process is starting by collecting the information data from a Computer Tomograph (CT), and is continuing with the part construction / re-construction of the future implant using a dedicated software program that is available at TUCN (the software is called MIMICS), the virtual implants being afterwards 3D printed using Selective Laser Sintering (SLS) technology at TUCN from Polyamide plastic material and finally a pair of mold is realized using Vacuum Casting technology at TUCN (figure 3.9), the real implant being realized after sterilization at UMPCN clinics in Cluj-Napoca (figure 3.10).

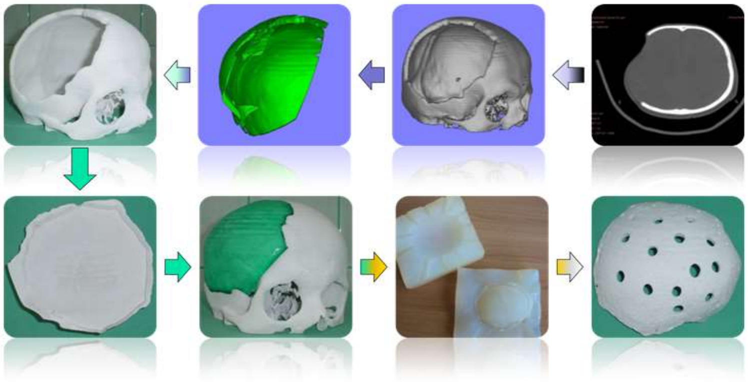

Fig 3.9. The steps of vacuum casting technology

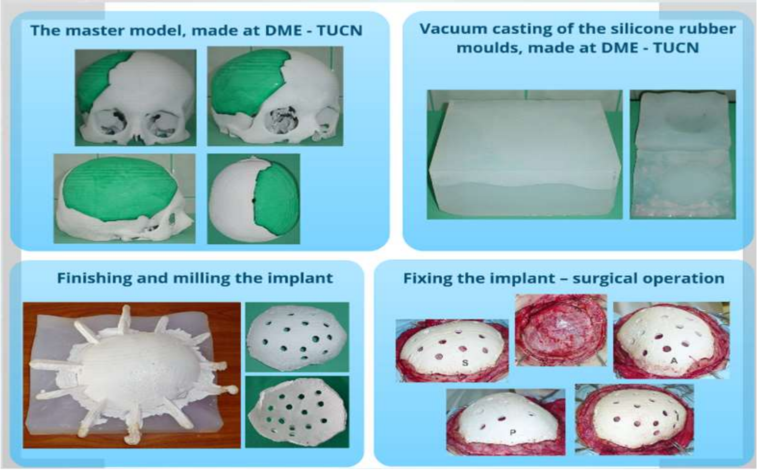

Fig 3.10. The real implant made using silicone rubber mould

The real implant made of polymethacrylate (PMMA) material has been produced by the doctors using the silicone rubber moulds produced by Vacum casting, supplementary holes being necessary to be realized in the case of the real implant as shown in the last image of Figure 3.10 for depressurization in the local area of implanting. In Figure 3.11 are presented few case studies that were developed at TUCN in case of real patients using the 3D printing and Rapid Tooling methods presented above. This solution has been successfully used in the last 25 years at the Technical University of Cluj-Napoca for surgical operations that were made by doctors of Hospital Clinics in Cluj-Napoca, Romania in case of more than 200 patients that needed such interventions.

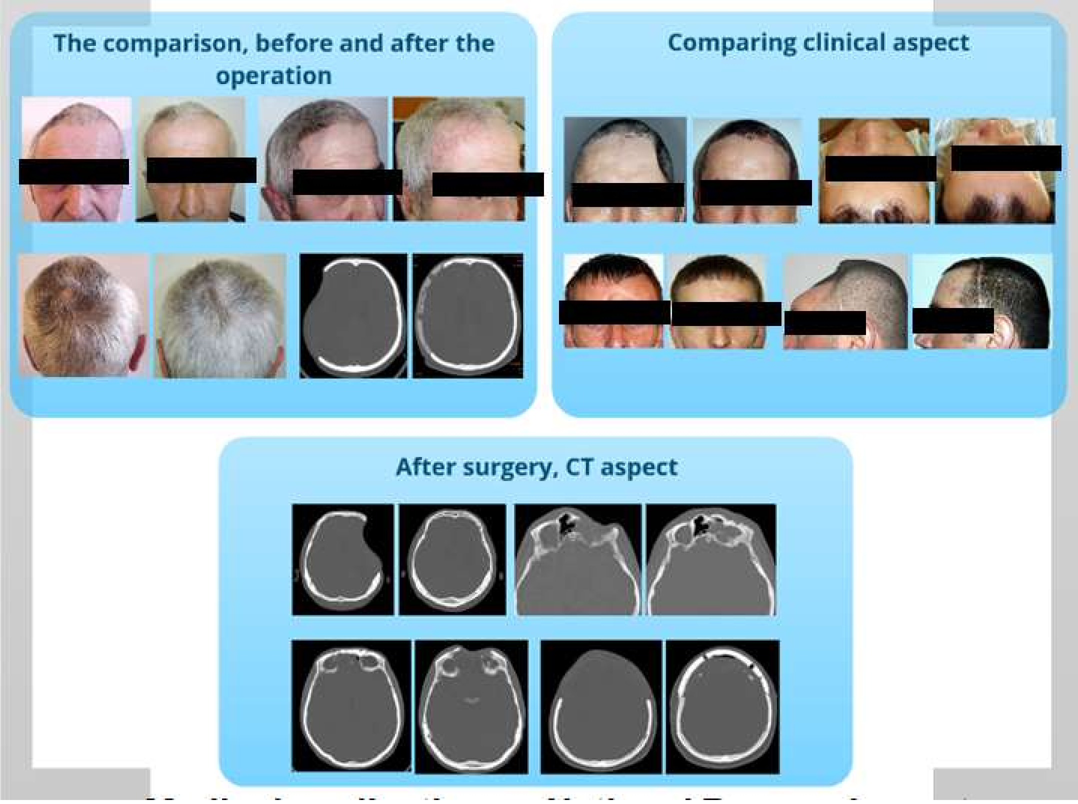

Fig 3.11. Case of real patients that have benefit of the solutions provided by the Technical University of Cluj-Napoca in cooperation with Hospital Clinics

4. Trends of Additive Manufacturing methods in the medical sector

4.1. Multi-material 3D printing and bio 3D printing technologies

Multi-material bio-printing of 3D constructs: blood-vessel-like structures, human organ-like constructs,(heart, kidneys, pancreas, lung, stomach, liver, etc.). In Fig. 4.1 are presented few of these examples that were developed in the last years with applicability in the medical domain. As one may notice the advance is impressive, since lot of progress has been done in using biomaterials in the process of 3D bioprinting.

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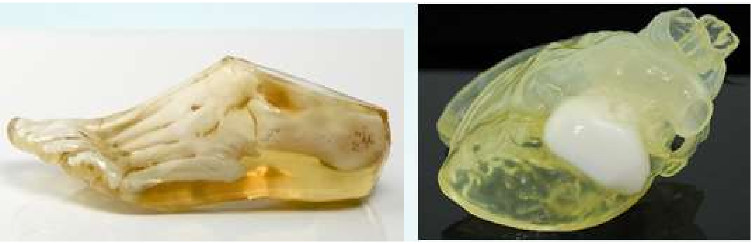


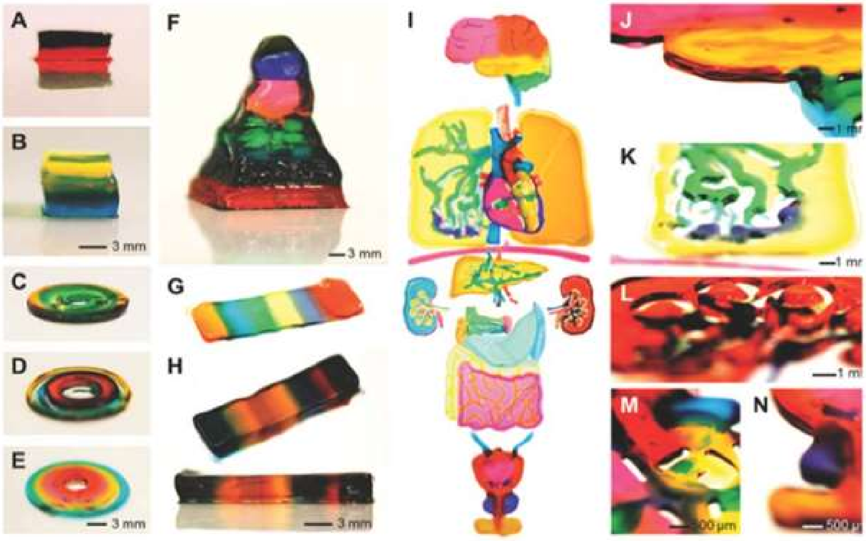
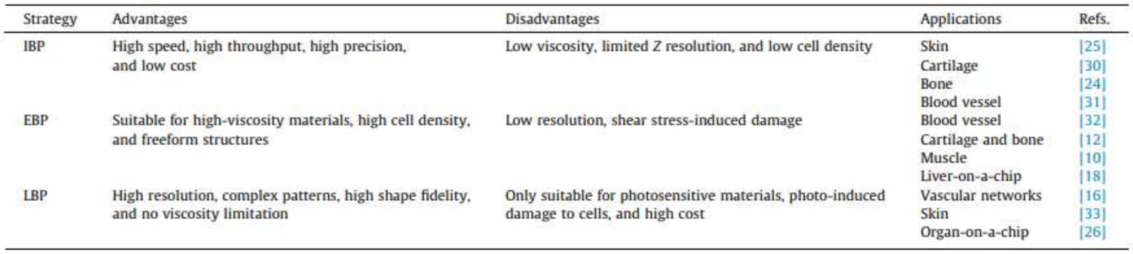


Fig.4.1. Multi-material bio-printing of 3D products [SUN20], [www36]

Three-dimensional (3D) bioprinting is a new trend of technology used in tissue engineering. It consists of depositing biomaterials, cells or biomolecules, to produce organs and tissues respecting the 3D printing principle. Using this technology it can be directly obtained parts of the body, like muscles, cartilage, skin, bone, vascular network, etc. (see figure 4.2). The most used bioprinting methods are: Inkjet-based printing (IBP), extrusion-based printing (EBP), and light-based printing (LBP)]. There are some advantages and disadvantages of these methods, a part of them being presented in table 4.1, as well as their applications [GAO15, SKA12]

Fig. 4.2. Applications of 3D bioprinting technology [www37]

Table 4.1. Comparison between different bioprinting methods.



Strategy	Advantages	Disadvantages	Applications	Refs.
IBP	High speed, high throughput, high precision, and low cost	Low viscosity, limited *Z* resolution, and low cell density	Skin Cartilage Bone Blood vessel	[25] [30] [24] [31]
EBP	Suitable for high-viscosity materials, high cell density, and freeform structures	Low resolution, shear stress-induced damage	Blood vessel Cartilage and bone Muscle Liver-on-a-chip	[32] [12] [10] [18]
LBP	High resolution, complex patterns, high shape fidelity, and no viscosity limitation	Only suitable for photosensitive materials, photo-induced damage to cells, and high cost	Vascular networks Skin Organ-on-a-chip	[16] [33] [26]

There are different strategies for Bioprinting, as shown in fig. 4.3:

- with a thermal / piezoelectric actuator;
- extruded polymer (melt or solution);
- laser assisted printing (LAP);
- stereolithography (SLA);
- two-photon polymerization (2PP);
- digital micro-mirror (DMD).

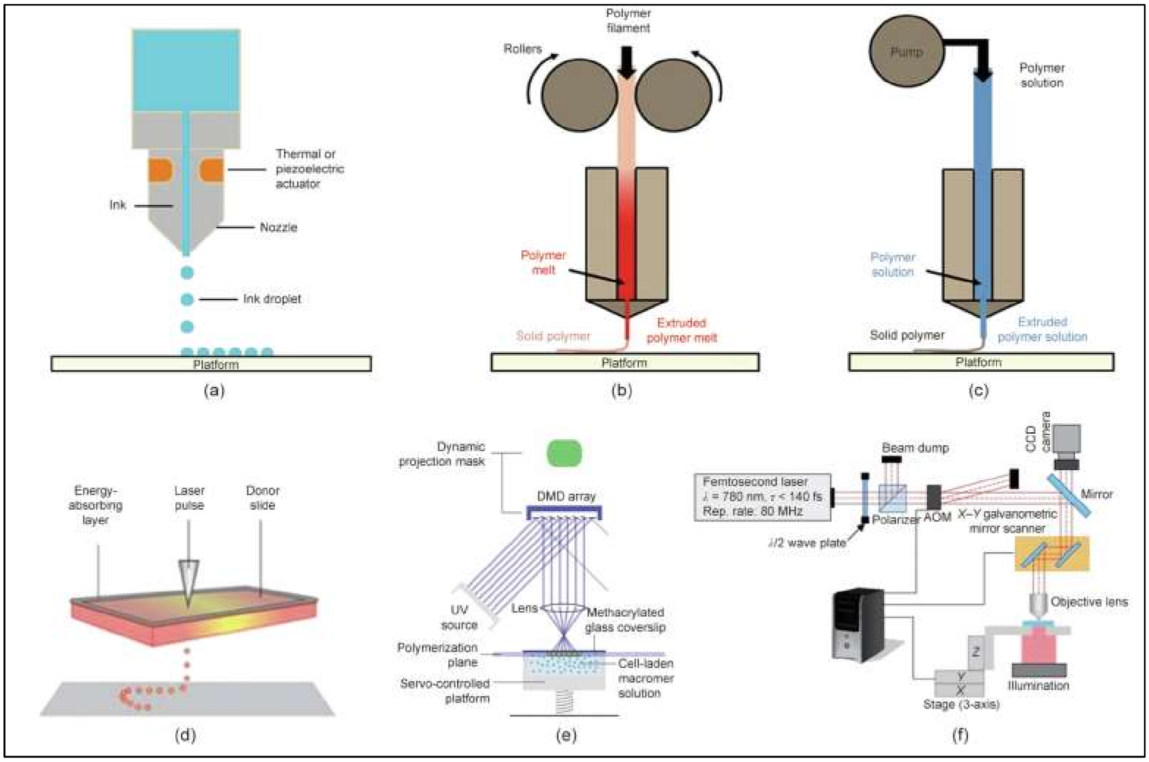


Fig.4.3. Different Bioprinting strategies [ZHA19]

Inkjet-based printing (IBP) is using a nozzle to eject the liquid droplets onto an stage electronically controlled. The forces applied are acoustic or thermal. The inspiration for this method came out from the normal printers HP. The bio-ink is initially liquid form and then is transformed into a solid state , so the viscosity must be low (3.5–12 mPa/s) and the cell must have a low density. This method is used for skin printing, bones, cartilage, blood vessels. Some advantages of the method are: low costs, high printing speed and high throughput. [GAO16]

If the viscosities of bioinks are higher or there is a higher cell densities (> 108 cells/mL), EBP method is recommended. This strategy uses biomaterials in beads of paste (melt-cure polymers and cell-supportive hydrogels) form for tissue reconstruction. A type of EBP is Fused deposition modeling that can melt multiple polymers (polycaprolactone – PCL, polyurethane- PU, polylactic acid – PLA).

Cell-free or cellladen hydrogels can be deposited by Direct ink writing (DIW) method.

Coaxial nozzles and development of multi-channel systems permit the applications in e microchannels ,vascular networks, etc .[CUI09] Bones and cartilages a hepatic toxicity assessment platform and muscle tissues, can be created using Multi-channel printing systems. From all the bioprinting strategies, the best characteristics regarding the high resolution, and lack of limitation in material viscosity has LBP (including laser-assisted printing – LAP, and stereolithography -SLA). LAP is used for skin-like constructs]. In the scientific literature there are multiple studies regarding the optimal parameters (laser wavelength and pulse durations) used for manufacturing of tissues. [CUI12]

Digital light processing (DLP) also known as SLA permits the manufacture of complex parts with high structural complexity, scalability, and flexibility. Through this method wide-range scales (50–250 lm) of vascular networks, heterogeneous hepatic models were achieved.

For smaller resolution (submicron resolution) is recommended two-photon polymerization (2PP). 2PP is used to develop fine 3D structures in microfluidic devices and to replicate submicron native-like microenvironments. In order to increase the speed of fabrication, multiple nozzle bioprinters were developed.

For the formation of tissues/organs there can be used bioinks, cell spheroids and tissue strands to reproduce the native tissues and organs (Fig. 4.4). [ZHA19] Myocardial tissues and vessels require a high cell density. Bioinks may play important roles in developing long-life functional tissues with dense vascular networks.

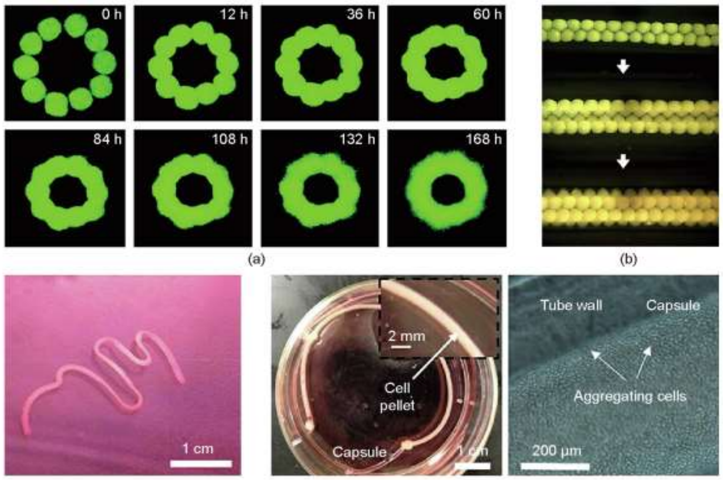


Fig. 4.4. Cell spheroids and tissue strands used as bioinks. (a, b) Cell spheroids (c, d) Tissue strands [ZHA19]

The 3D cell-printed structure has applications in various areas including tissue engineering, in vitro drug screening and tissue/cancer model. An example of tissue printing with dECM bioink encapsulating living stem cells is presented in figure 4.5. [LEE14]

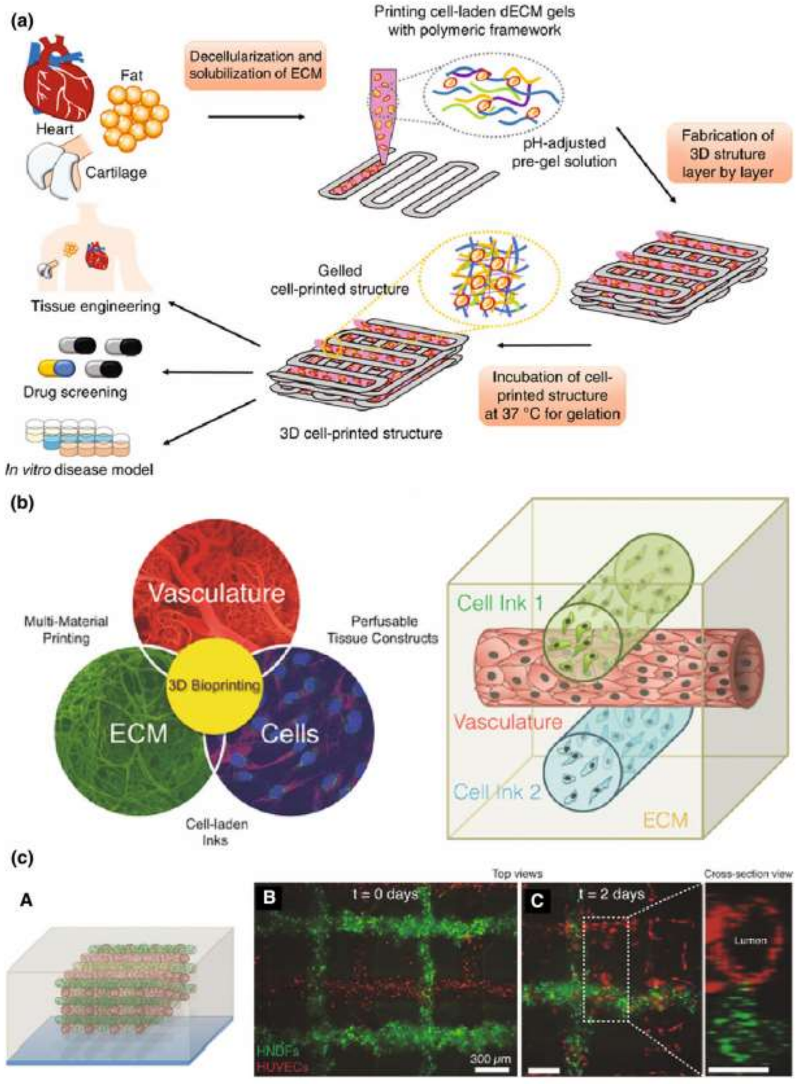


Fig. 4.5. 3D bioprinting of biomimetic extracellular matrices (ECMs). [ZHA19],[VAN16]

The development in vitro of the **vascularized 3D tissues** represents a revolution in domain. In the last years, multiple studies were made on this field for removing the technological limitations. Following these studies multiple vascularization networks were designed and manufactured. An example of the vascularization networks from a heart is presented in Figure 4.6. The 3D bioprinting was done using porcine cartilage, heart tissue, and human adipose tissue. The studies proved that not only the cell structure is important, but also the binder used in the manufacturing process. It was concluded that for a good compatibility similar to the biological environment, binder obtained from biological structures must be used.

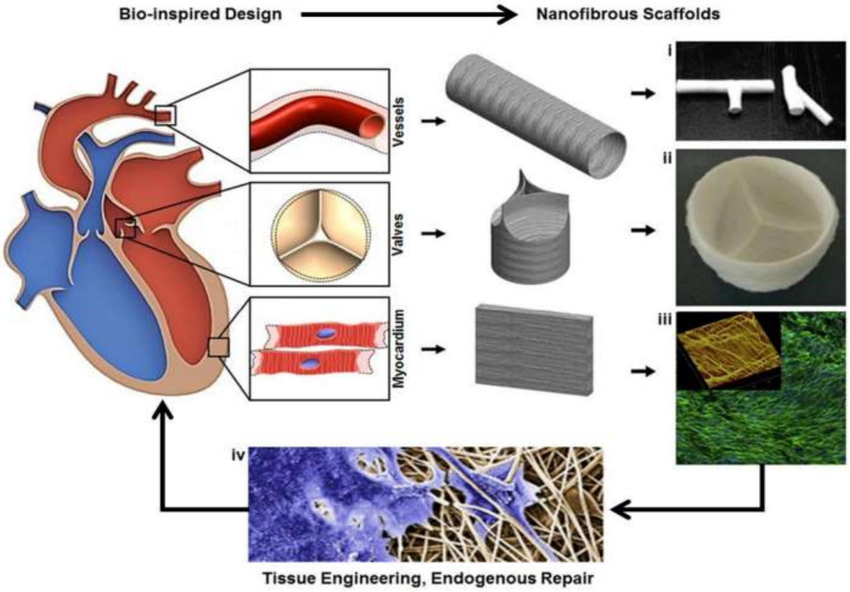


Fig.4.6. The vascularization networks from a heart [GAN16]

3D Bioprinters found applications also in **Cartilages and bones (**tissues with high mechanical strengths in human bodies). There are researches for improving the mechanical properties of the obtained tissues and the interface between the implant and the nearly tissue as shown in Figure 4.7. [CAP16]

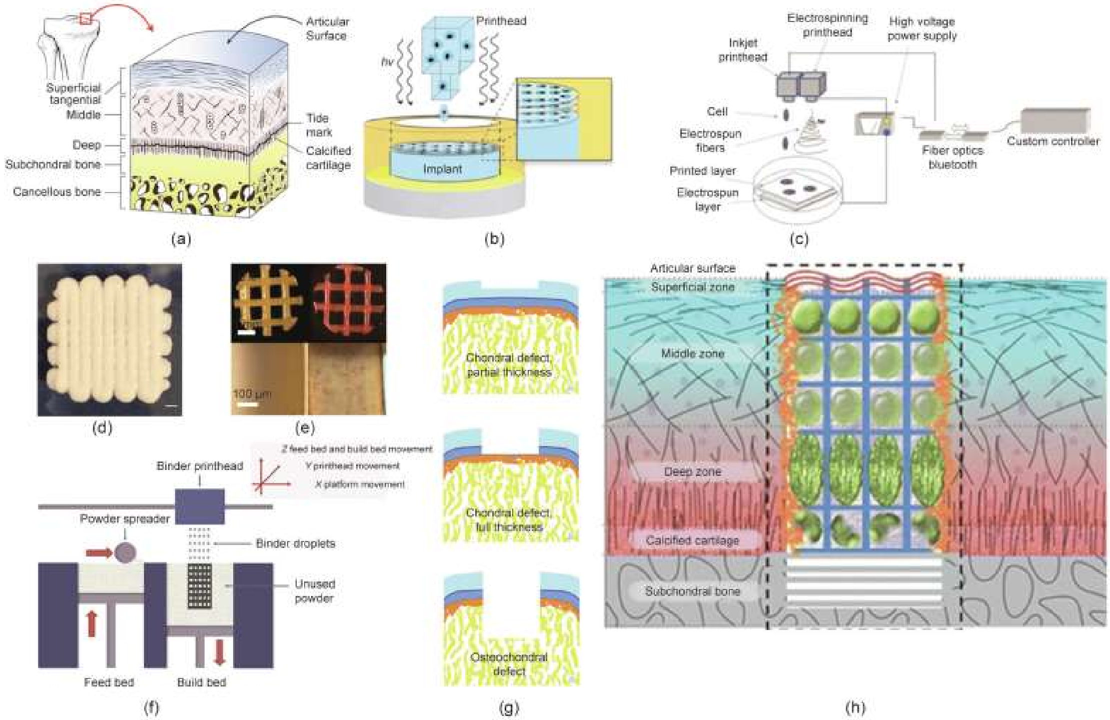


Fig. 4.7. 3D bioprinting of cartilages and bones. [ZHA19]

Articular cartilages is the most stressed part from the human body and is very often exposed to damage. It has a complex structure and can be manufactured from different bioinks (alginate and agarose hydrogels). Nanofibrillated cellulose, PLA nanofibers, can be used to improve cell density and reinforce the mechanical strength. Some examples for bone regeneration models are presented in figure 4.8.

Another application of the 3D Bioprinting is represented by **skin** formation, which have many applications in dermatology, immunology, and surgery. Artificial skin was obtained by multiple procedures for the superior layers of the skin (epidermis and dermis), as presented in figure 4.9. The printed skin tissue demonstrated better shape fidelity, compared with the manual deposition model, and exhibited distinct layers of the epidermis and dermis. [LEE09 KIM11]

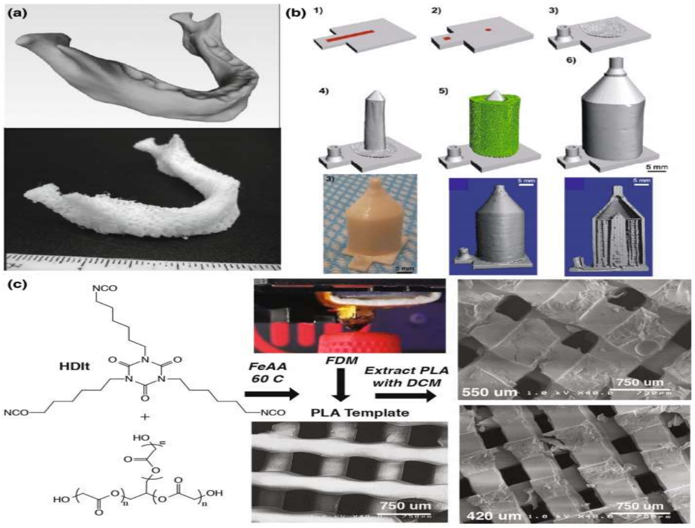


Fig. 4.8. **3D-printed models of bone regeneration**. (a) An atomically shaped scaffold. (b) 3D printing of Tissue-Engineered Constructs (TEC) comprising a scaffold and bioreactor. (c) Schematic of the t-FDM fabrication of 3D scaffolds, by a MakerBotReplicator2 3D printer [VAN16]

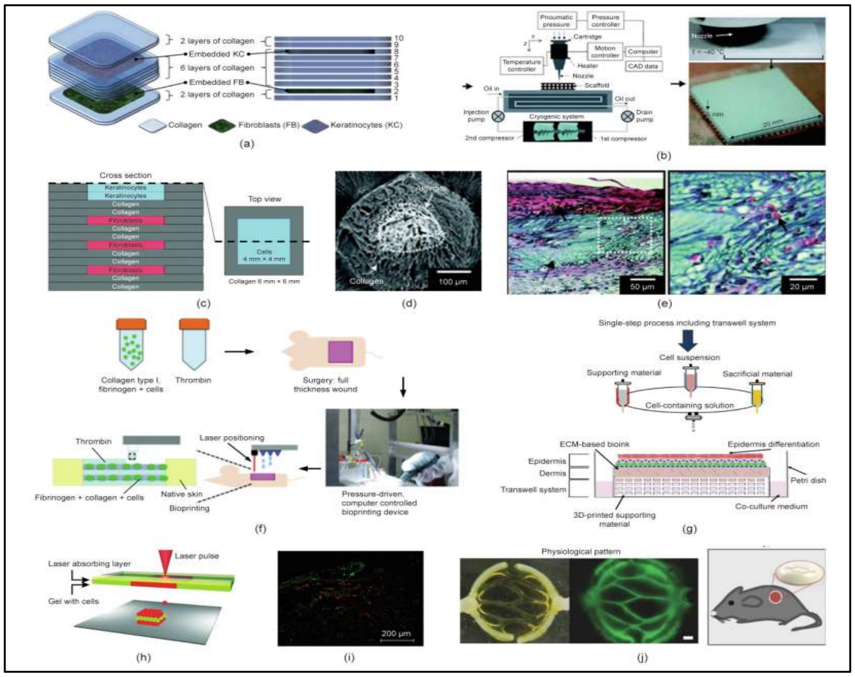


Fig. 4.9. 3D bioprinting of skin: (a–e) EBP for skin reconstruction. (f, g) IBP for skin reconstruction, (h–j) LBP for skin reconstruction. [LEE09], [KIM11], [ZHA 19]

<u>Muscle printing</u> has attracted research interest due to its potential in the treatment of muscle diseases and injuries, as well as in drug studies, Fig. 4.10. Manufacturing of the artificial muscles structure requires a lot of research because the muscle cells, the nervous and vascular system, the fascia, the tendons must be printed. [MER15][KHA16]

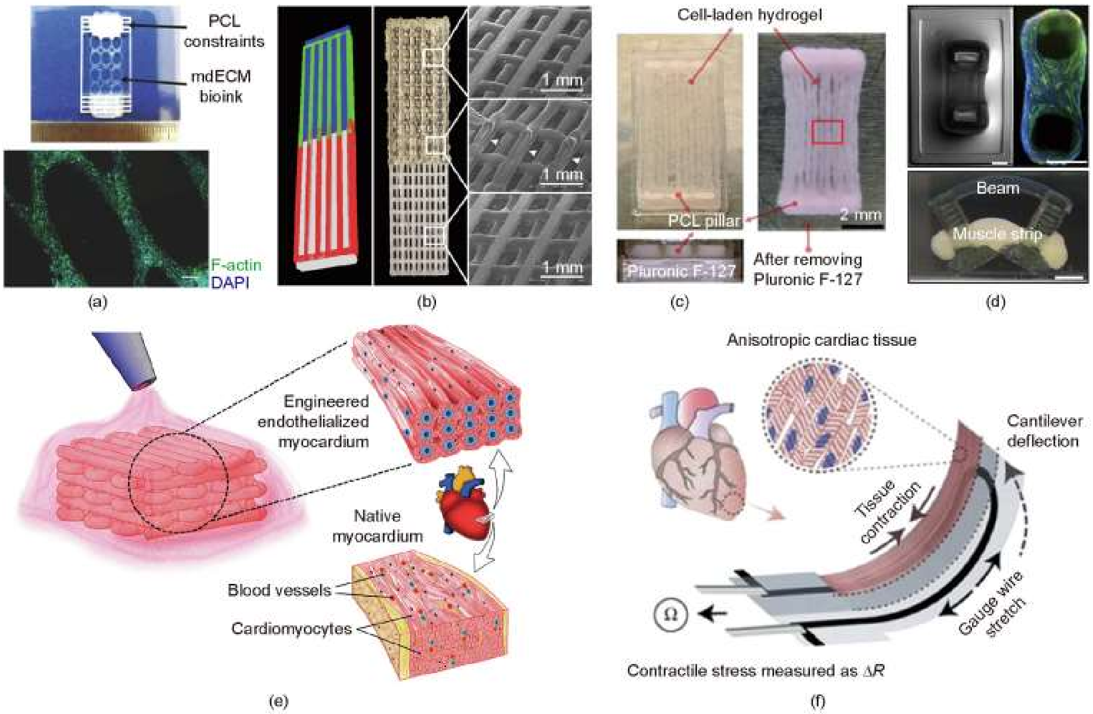


Fig. 4.10. 3D bioprinting of muscular tissues. (a–d) 3D bioprinting of skeletal muscles, (e, f) 3D bioprinting of cardiac muscles. [LEE09], [KIM11] [ZHA 19]

The artificial tissue can be combined with microfluidic technology to obtain drug discovery platforms. Studies were developed on liver on-a-chips and heart-on-a-chips drug screening and toxicity testing. Different structures were made on a platform that embedded derived hepatic progenitor cells with human umbilical vein endothelial cells and adipose-derived stem cells in a hexagonal architecture using DLP method. This method has been preferred since it provides the highest resolution and highest constructing speed among all bioprinting strategies, permitting the rapid manufacturing of chips and the construction of heterogeneous structures (see Fig.4.11). [MER15][KHA16][CVE14]

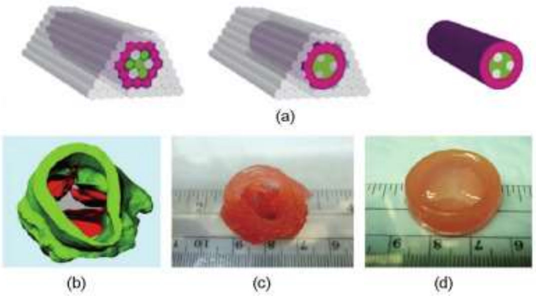


Fig. 4.11. Bioprinted hollow tissues. (a) Nerve graft with multiple lumina. (b–d) Heart valves. [ZHA19]

Some research was focused on construction of a heart-on-a-chip by directly printing endothelial cells with hydrogels and seeding cardiomyocytes onto the endothelial bed as one may notice in Fig.4.12.

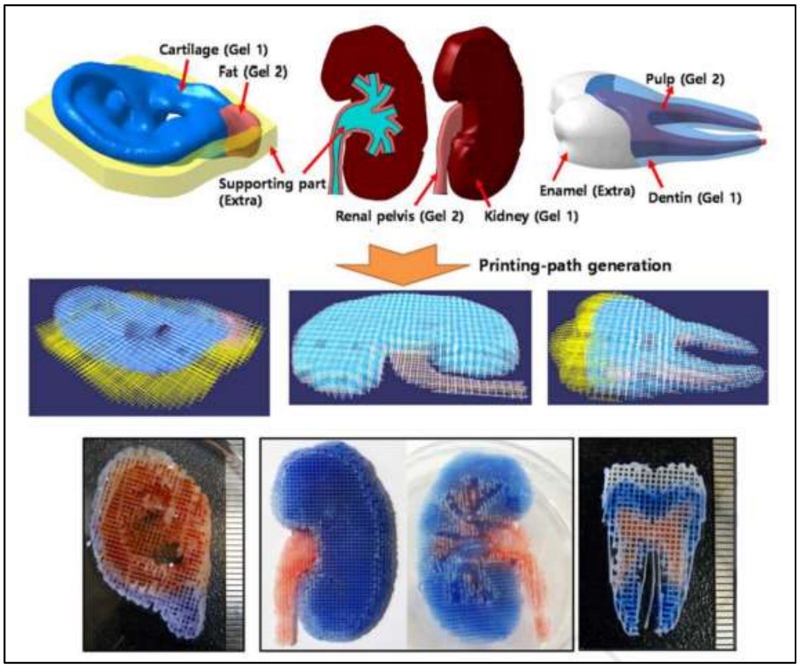


Fig. 4.12. CAD model acquisition and generation of the printing path for different types of organs. [GON19]

The chemical composition of the cell-laden support is very important in the process. The used material can be as a scaffold with the ability to encapsulating cell or drugs. The scaffold allows to deposit different materials and to immobilize cell types (see Figure 4.13). The disadvantage of the method is representing by the shear stress (from the variably sized nozzles) that can have a negative impact on cell viability during the printing process.

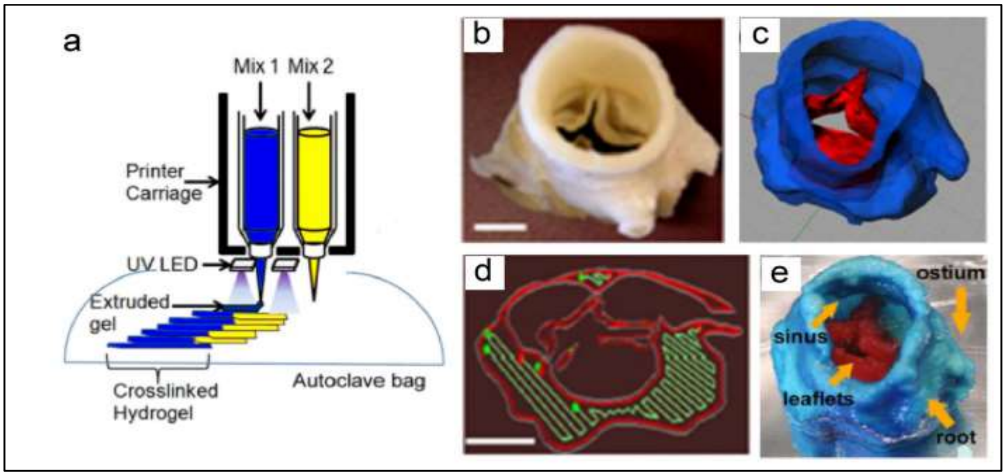


Fig. 4.13. Bioprinting of scaffolds for heart valve tissue engineering [JAN14]

4.2. 4D printing method for medical applications

4D printing is attracting a lot of interest since the first time it was conceptualized in 2013. The idea of 4D printing derived from the interdisciplinary research and the fast growth of smart materials, additive manufacturing and design. Compared with the normal objects created by 3D printing, the 4D printing process creates a printed structure how can change its function or configuration in time as a response to external stimuli like, water, light, temperature, etc. as shown in Fig.4.14. Further om, some systems and materials used in 4D printing were developed, focusing on potential mechanisms and applications of this method for medical applications. 4D printing of multifunctional materials and both single multiple materials for shape changing is a trend foreseen to be reached through this method. [MOM17].

This project has been funded with support from the European Commission. This publication [communication] reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Fig.4.14. 4D printing method [www38]

Using a Connex Objet500 printer, it was possible to develop by 4D printing method a series of hinges with a rigid plastic base and a hydrogel that swelled when exposed to water, as shown in figure 4.15. Figure 4.15 (a) shows the black lateral springs that represent the rigid bars and discs (plastic) and the red springs (hydrogel) that represent the links that make the joint fold. . As shown in Figure 5.15 (b) a multi-material strand printed in 4D can automatically fold into a cube. Figure 5.15 (c) shows a structure with hydrogels placed between the rigid layer (top) and the elastomer layer (bottom). The small holes are designed in the elastomer layer as pathways for the water to trigger a change of shape. After placing the structure in cold water, the hydrogel swelled, but the deformation of the structure was limited by the rigid SMP. Upon heating, the stiffness of the SMP decreased, which relieved the stresses and resulted in bending when heated. Subsequent cooling and drying of the hydrogel would block the shape of the bend, which would return to its original shape when heated again.

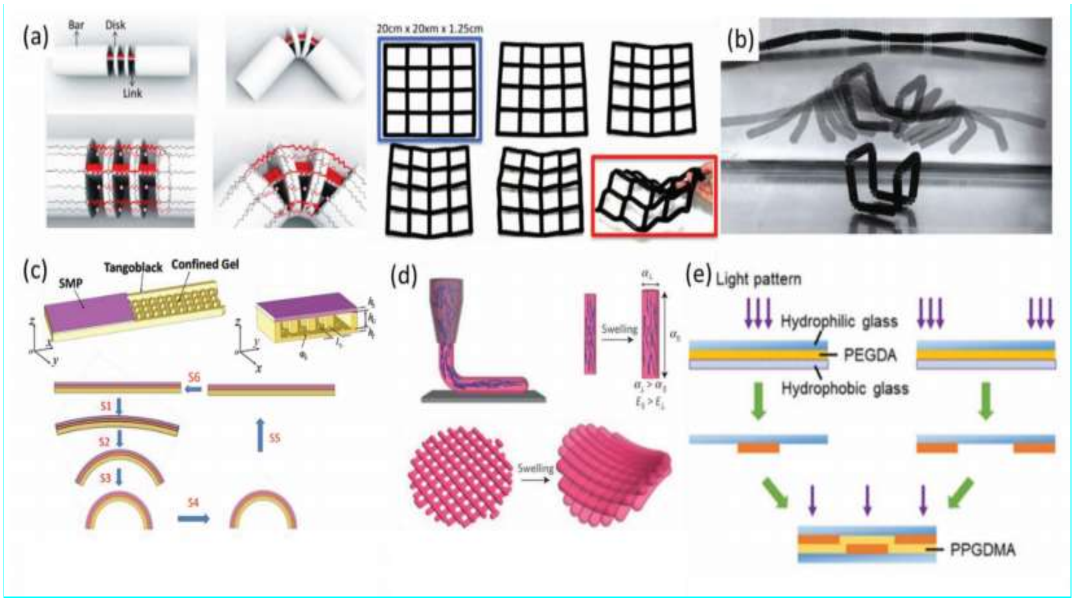


Fig. 4.15. 4D printing of water activated multimaterial:
a) grid that deforms into a hyperbolic surface; b) self-folding of a multimaterial; c) Reversible actuation component; d) The shear-induced alignment of cellulose fibrils; e) Fabrication process of the hydrophilic/hydrophobic composite structures. [KUA18][RAV15]

As shown in Figure 5.15 (d), due to the high shear force generated during the printing process, when the ink flows through the deposition nozzle, the nanofibrillated cellulose (NFC) undergoes shear-induced alignment. Printing filaments with anisotropic stiffness in the longitudinal direction (along the printing path) and the transverse direction The orientation makes the 3D printed composite hydrogel have local anisotropic swelling behavior. As shown in Figure 5.15 (e), two separate poly(ethylene glycol) diacrylate (PEGDA; hydrophilic) patterns are cured between glass slides under different light patterns, and the cured pattern attached to the hydrophilic glass is Demoulding. Then the poly(propylene glycol) dimethacrylate (PPGDMA) liquid resin is injected into the space between the two PEGDA patterns, and then the entire structure is photocured. After treatment in water, the strain mismatch between the hydrophilic PEGDA rubber and the hydrophobic PPGDMA rubber of the two-layer composite caused a controlled shape transition. Compared with the traditional hydrogel water response design, this composite material provides excellent driving speed and driving force due to the rubber nature of the hydrophilic material.

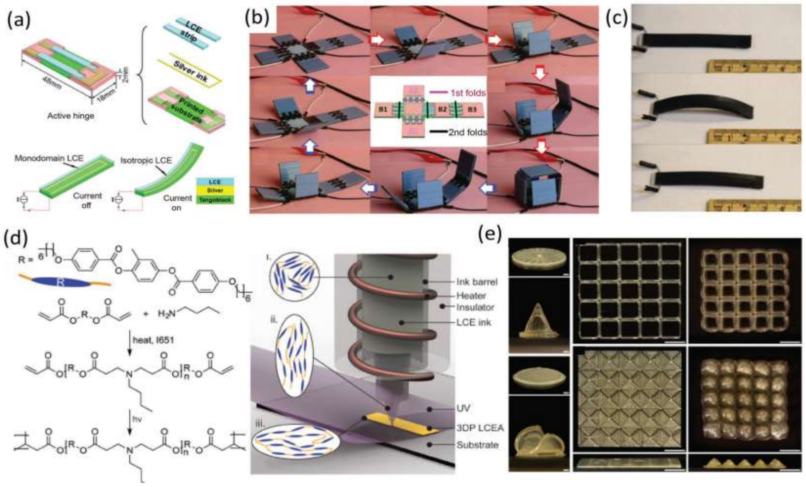


Fig. 4.16. 4D printing of liquid crystal elastomer: a) Schematic diagram of a laminated hinge; b) A snapshot of the folding and unfolding process; c) A snapshot of the movement of the soft crawler; d) One-pot synthesis of photopolymerizable LCE ink; e) Programmable shape deformation of LCE actuator [KUA18]

4D printing of SMP composite materials were nowadays developed and used for medical applications. [KUA18][WU16 YUA17 CON14] SMPs are a group of materials that have been explored for deformable structural applications. In addition, the feature of programmability distinguishes SMPs from hydrogels. One of the early work of SMP-based 4D printing is based on the PAC. PAC is printed by a multi-material Connex Objet260 3D printer and is composed of glassy polymer fibers (VeroWhite) in a rubber matrix (TangoBlack). The glass transition temperature of glassy polymers is 60 °C, so they are used as SMPs. Depending on the fiber distribution and direction, a variety of complex 3D configurations can be obtained, including curved, coiled, twisted, and folded shapes. This composites can be used as smart hinges, enabling active origami to create complex 3D structures. An origami airplane can be assembled by folding a printed flat SMP composite sheet with multiple smart hinges, Figure 4.18 (b). Complex movable origami structures, such as tables, Figure 4.18 (c). Using a similar strategy, Wu et al. [WU16] demonstrated the design of SMP composites that can present multiple shapes through digital SMP. And so on, this provides a huge advantage in terms of material availability and design freedom. Wu et al. used digital SMP fibers with different Tg values to design and print laminated composite structures with different SMP fibers to achieve multiple shape changes at different .[CON14, WU16,YUA17]

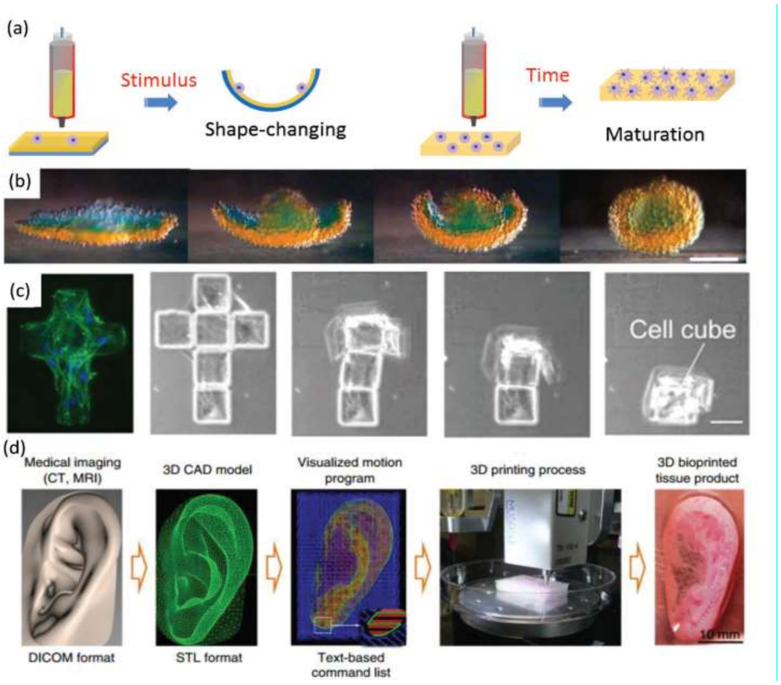


Fig. 4.18. Biomedical applications of 4D bioprinting. a) A schematic diagram of a 4D bioprinting method b) flower-shaped network spontaneously folded into a hollow sphere. c) Continuous images of regular quadrilaterals, filled with 3D cells d) The imaging/CAD/printing process of tissue or organ 3D bioprinting [KUA18]

The fact that printed 3D biocompatible materials or living cell structures evolve over time can be referred as 4D bioprinting. As shown in Figure 4.18 (a), 4D bioprinting includes the maturation of deformed biological materials and engineered tissue structures realized by 3D printing. Using microplates without flexible joints, hollow microstructures, such as cubes, can fold themselves, Figure 5.18 (c). The 3D printing of porous biological scaffolds shows great potential for soft tissue reconstruction. Kang et al. [KAN16] reported an integrated tissue and organ printer (ITOP), which can make Any shape of stable, human-scale tissue structure. As shown in Figure 5.18 (d), it shows that this method can be used for realizing mandible and skull, cartilage and skeletal muscle. 4D bioprinting shows great potential in future biomedical applications, such as tissue engineering, organ regeneration, drug delivery, and the construction of functional organs suitable for transplantation. [KUA18,KAN16]

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