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3D PRINTING TECHNOLOGIES, MATERIALS AND SOFTWARE APPLICATIONS

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MAKER SCHOOLS
3D Design for Education

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Introduction

3D printing or additive technology is the process of creating three-dimensional objects with arbitrary geometric shapes based on digital models. The concept of 3D printing involves the construction of the object by sequentially applying layers within the contour of the model. 3D printing is thus the complete opposite to traditional methods of mechanical production and processing such as turning, milling, cutting, etc. in which the product is formed by removing excess material.

We will briefly outline the emergence and development of 3D printing. In 1984, in the United States, Charles Hull developed the stereolithography technology (SLA) for printing 3D objects from photopolymerizing composite materials based on digital models. Two years later, he was granted a patent for SLA, founded the company "3D-Systems", and developed the first 3D printer called a "Stereolithography machine". In 1988, 3D-Systems developed the first model of a 3D printer (SLA-1) designed to be implemented in serial production and targeted at consumers.

In 1987 Carl Deckard from the University of Texas developed and patented a method for selective laser sintering (SLS). In 1989 Scott Crump, co-founder of Stratasys Inc., invented the Fused Deposition Modeling (FDM) method, the most widely used 3D printing methods. The FDM patent was granted to Stratasys in 1992. In Europe in 1989, EOS GmbH was founded in Germany by Hans Langer. EOS's research and development focused on the laser sintering process (LS). Today, EOS's systems are recognized worldwide for their quality production for industrial prototyping and 3D printing production applications. EOS sold its first Stereos system in 1990. The company's Direct Metal Laser Sintering (DMLS) process is the result of a project implemented together with Electrolux Finland. Other 3D printing technologies and processes emerged during the years, namely Ballistic Particle Manufacturing (BPM), originally patented by William Masters; Laminated Object Manufacturing (LOM), originally patented by Michael Feygin; Solid Ground Curing (SGC), originally patented by Itzchak Pomerantz and others; "three-dimensional printing" (3DP), originally patented by Emanuel Sachs and others.

In sum, all basic technologies for 3D printing were developed and patented in the 80s and 90s of the last century. At that time, conditions for the intensive development of this part of science and technology were not yet present.

In 1994, students at the Massachusetts Institute of Technology modified an inkjet printer that created 3D images. It is at that time that the concept of 3D printing and the term 3D printer emerged. The company Z Corporation obtained a license from MIT to use the technology. Z Corporation was acquired by 3D Systems in 2012. The history of the 3D printer development continued with the emergence of the PolyJet technology based on the use of photopolymer resin. In this technology the print head of the printer "paints" a layer of the model with the help of light-sensitive resin, which is illuminated by a lamp.

Over time, the development of the 3D printing industry has accelerated, new companies manufacturing 3D printers emerged, new materials and approaches started to be used, the devices' sizes and prices decreased. The details printed by modern printers are characterized by high mechanical strength and can be used as finished products. The speed of 3D printing has also significantly increased. In the initial period of 3D printers' development, their price was quite high, and the printers were available only for larger companies. Currently, everyone can get a 3D printer at home, the price of which varies from EUR 300 to EUR 1,000.

This learning resource covers the basic technologies and materials used in 3D printing, the main stages in 3D modelling and printing, software products for creating 3D models and for layering and the application of 3D printing.

3D printing technologies

Classification of 3D printing technologies

The 3D printer is a device that performs three-dimensional printing and allows you to create material objects based on 3D models. The design features of the 3D printer depend entirely on the additive technology embedded in it. Automated additive technology is impossible without information about the geometry and the location of the elements of the object that will be printed. This information is represented by digital 3D models. They are created by computer graphic design or by 3D scanning.

During printing, the printer reads the 3D print file in STL format containing 3D model data, and sequentially applies layers of liquid, powder, or sheet material, building a 3D model from successive cross-sections. These layers, corresponding to the virtual cross-sections in the computer model, are joined together to create the object with the specified shape. The main advantage of this method is the ability to create geometric shapes with virtually unlimited complexity.

The printer resolution refers to the thickness of the applied layers (along the Z axis) and the accuracy of positioning of the print head in the horizontal plane (along the X and Y axes). The resolution is measured in DPI (dots per inch) or in micrometers. The typical layer thickness is 100 µm and some devices can print 16 µm thick layers. The resolution on the X and Y axes is comparable to that of ordinary two-dimensional laser printers.

Traditional production methods such as injection molding or pressing can be cheaper for the production of products in large quantities. Additive technologies on the other hand have advantages in small-scale production, as they allow for greater design flexibility and higher economy per unit of product produced. In addition, desktop 3D printers allow designers to create concept models and prototypes without leaving the office.

The technological features of the three-dimensional printing process depend on the technology of additive production. The ISO/ASTM 52900 standard was established in 2015 to standardize 3D printing methods' terminology and classification. The standard regulates seven technological processes. The classification of the main technologies and methods used in 3D printing, as well as the materials used, are shown in Table 1.1.

Table 1.1: Classification of 3D printing technologies

Technological process	**Description**	**3D printing method**	**Used materials**
Extrusion of material	Additive manufacturing process in which the material is fed through a nozzle.	Fabrication by the method of fusion of filament (Fused Filament Fabrication - FFF) or layering (Fused Disposition Modelling - FDM)	Thermoplastic polymers (polylactide, acrylonitrile butadiene styrene and others)
Vat Polymerization	Additive manufacturing process in which a liquid photopolymer in a vat is selectively cured by light activated	*Stereolithography* - SLA, *Digital Light Processing* - DLP	Photopolymers

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	polymerization.		
Melting of powdered material	Additive manufacturing process in which heat energy selectively melts portions of a layer of powdered material.	Selective Laser Sintering - SLS, Direct Metal Laser Sintering - DMLS, Selective Laser Melting - SLM, Electron Beam Melting - EBM.	Thermoplastic polymers, metal powders, ceramic powders, titanium alloys, cobalt-chromium alloys, stainless steel, aluminum
Inkjet printing of material	Additive manufacturing process in which drops of the material are selectively deposited and cured on a substrate.	3D inkjet printing (*Material Jetting* - MJ), *Drop on Demand* - DOD	Gypsum, plastics, metal powders, sand mixtures
Binder Jetting	Additive manufacturing process in which a liquid binder is selectively deposited to join portions of powder material	Binder Jetting - BJ	Powder materials and binder
Directed energy and material deposition	Additive manufacturing process in which concentrated heat energy is used to melt materials in layers	Selective laser metal deposition LMD	Thermoplastic polymers, metal alloys
Laminated object manufacturing	Additive manufacturing process in which sheets of material are joined to form the object	Ultrasonic Additive Manufacturing - UAM, Laminated Object Manufacturing - LOM	Paper, metal sheet, plastic tape.

3D printing technology by extrusion of the material (Fused Disposition Modelling - FDM; Fused Filament Fabrication - FFF)

3D printing by extrusion or layering (FDM/FFF) was developed in the late 80's by Scott Crump and was popularized by the company Stratasys Inc. The FDM patent was granted to Stratasys in 1992. After the expiration of the patent validity, new developers of 3D printers appeared, as well as companies using this technology. As a result, the cost of devices has been reduced more than twice compared to the period of invention of the technology.

The process of printing by the method of layer-by-layer deposition consists in creating layers by extrusion of rapidly cooled material in the form of microdroplets or a thin jet. The extrusion head heats the material to the melting temperature, and the molten mass is then fed through a nozzle. The extrusion head is driven by a stepper motor or servomotor, ensuring positioning of the extrusion head in three planes. The movement of the extrusion head is controlled by a microcontroller with the appropriate software.

The block-diagram of an extrusion type 3D printer device is shown in Figure 1.1.

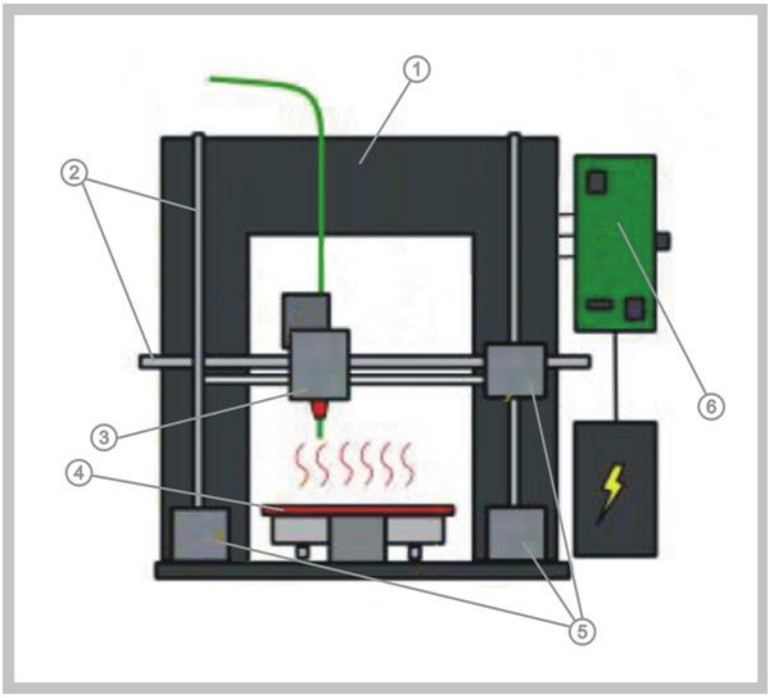

Figure 1.1. Block diagram of the extrusion type 3D printer device

1 – 3-D printer case, 2 – Guides attached to the case, 3 – Extrusion head; 4 – Build platform; 5 – Stepper motors; 6 – Control

The technological process starts with the processing of the three-dimensional digital model. The model, in STL format, is divided into layers and oriented in the most appropriate way for printing (Figure 1.2). Some devices allow different materials to be used during printing. For example, it is possible to print the model from one material and print the supports from another more easily soluble material that which allows us to easily remove the supporting structures after the completion of the 3D printing process. An alternative option for printing is to print the same plastic material with different colors. The item is prepared by extrusion and application of microdroplets of molten thermoplastic polymer with shaping of successive layers, hardened immediately after extrusion.

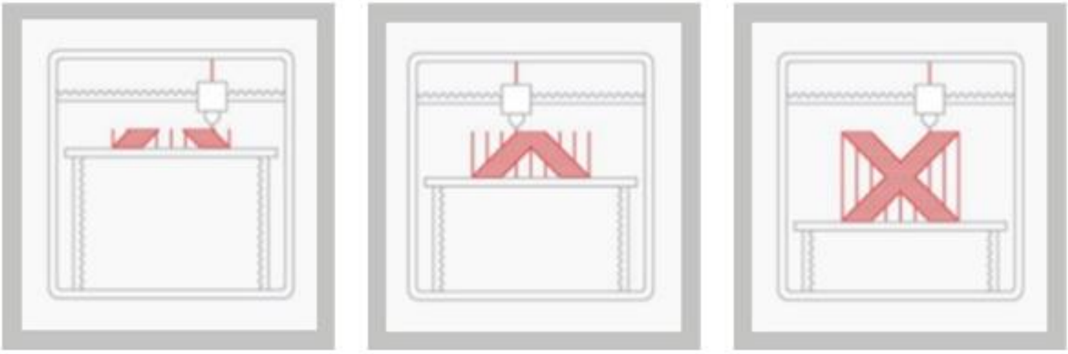

Figure 1.2. 3D extrusion printing process

The plastic filament is unwound from the spool and fed into the extruder - a device equipped with a mechanical drive for feeding the filament, a heating element for melting the material and a nozzle through which the extrusion takes place directly. The heating element serves to heat the nozzle, which melts the plastic filament and deposits the molten material on the model that is being printed. The upper part of the nozzle is cooled by means of a fan to create a sharp temperature gradient to ensure a smooth supply of material.

The movement of the extruder in the horizontal and vertical planes is done under the control of algorithms similar to those used in machines with digital program control. The nozzle moves along a trajectory set by the automated design system. The model is built layer by layer from the bottom up.

The extruder, also called an extrusion head, is driven by stepper motors or servo drives. The coordinate system most often used in FDM technology is the Cartesian system, built in a rectangular three-dimensional space with X, Y and Z axes. An alternative is the cylindrical coordinate system.

As the most common and affordable way for 3D printing, this method can use a wide range of materials. Different types of polymers such as acrylonitrile butadiene styrene, polycarbonate, polylactide, polyphenylene sulfone, etc. are used as extrusion printing materials. The low cost of materials and equipment, as well as the simplicity of operation, result in a competitive price of this type of 3D printing in the production of random thermoplastic parts. This method is often the first that people are introduced to and it constitutes the largest base of 3D printer equipment in the world. The extrusion technology that can use various materials is the most popular method for rapid prototyping and other, usually non-commercial, functional applications.

The main limitations of this type of 3D printing are related to the details' anisotropy. Multi-layered 3D printing leads a situation in which in the different planes the details have different mechanical properties. The location of the part during printing affects how mechanically strong it will be in each plane. The parts' mechanical properties are also affected by the degree of filling. The higher degree of filling gives the part strength, but also increases the time and cost of printing.

Extrusion-based 3D printing is used both in low-cost 3D printers and in high-tech production equipment. Most low-cost 3D printers are technically similar to their high-tech industrial counterparts, but their potential differs. The main difference between industrial and desktop printers is in the range of available printing materials. Industrial 3D printers can print with the same standard thermoplastics that we use in desktop ones, but they can also print details from more complex thermoplastics.

The industrial 3D extruder printers maintain a controllable environment and are able to automatically adjust the printer parameters to the print material. The controlled environment assumes that the details are printed in a closed space with adjustable temperature and humidity. This reduces the time it takes for the parts to be cooled, limiting the possibility of distortions and deformations. Most industrial extruder printers use double extrusion, allowing supports to be printed from soluble material. Thanks to the controlled environment, industrial extruder printers produce details with great accuracy and quality.

Desktop extruder printers are affordable in terms of price and give the possibility for fast 3D printing. Printing accuracy is acceptable for a number of applications and purposes. Due to improvements in hardware, materials and software, the gap between industrial and desktop extruder printers is gradually narrowing. They are an ideal prototyping tool.

3D printing technology through Vat polymerization (Stereolithography - SLA; Digital Light Processing - DLP)

Vat polymerization technology uses liquid photopolymer resin, which is cured by a light-activated process. The main Vat polymerization methods are SLA (Stereolithography) and DLP (Digital light processing).

Stereolithography (SLA)

Stereolithography is a technology of additive manufacturing of products from liquid photopolymer resins. The term "stereolithography" was proposed in 1984 by Charles Hull, who patented a method and equipment for producing details by sequential layering of photopolymeric material. The Charles Hull patent described the use of an ultraviolet laser beam directed at the surface of a volume filled with liquid photopolymer. The illumination with the laser beam hardens the material at the points of contact, which allows the contour of the manufactured part to be drawn layer by layer (Figure 1.3).

In 1986, Charles Hull founded the company 3D-Systems for the commercial development of new technology. 3D-Systems is among the world leaders in developing and supplying additive manufacturing technologies, and stereolithography technology is the first patented and commercially available 3D printing technology.

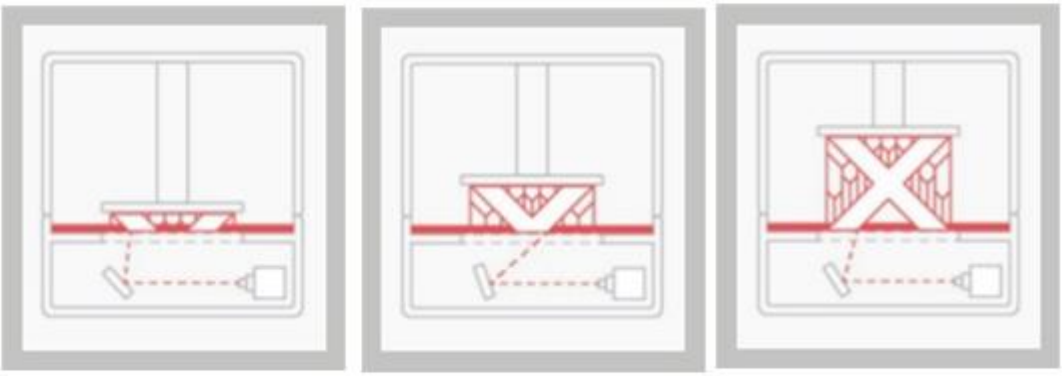

Figure 1.3. 3D printing process by Vat polymerization

The process uses mirrors called galvanometers or galvos (one located on the *X* axis and one on the *Y* axis) to quickly point the laser at the tub space, which is the printing area. This process breaks the project layer by layer into a series of points and lines that are transmitted to the galvos as a set of coordinates. Most SLA printers use solid-state lasers. The SLA printer scheme is shown at Figure 1.4.

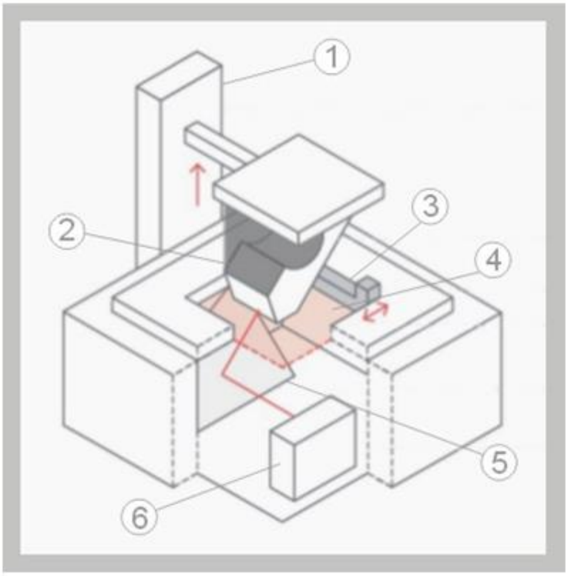

Figure 1.4. Scheme of SLA printer

1 – Elevator; 2 – Printed part; 3 – Sweeper; 4 – Liquid photopolymer; 5 – X-Y Scanning mirror; 6 – Laser

Digital light processing (DLP)

The DLP technology is similar to the SLA technology in terms of how the part is produced. The main difference is that DLP uses digital LED projection to irradiate the entire layer at once (or to perform multiple irradiations in the case of larger printed parts). Because the projector is a digital screen, the image of each layer is composed of square pixels, which forms a layer of small rectangular bricks called voxels. DLP technology achieves shorter printing time than SLA, as the entire layer is irradiated at once, instead of performing continuous laser tracking of a cross-sectional area. The light is projected onto the resin by means of LED screens or an ultraviolet light source (lamp) directed at the printing surface by a Digital Micromirror Device (DMD). DMD is an array of micromirrors that control where light is projected and form the light structure on the print surface. Figure 1.5 shows a DLP printer scheme.

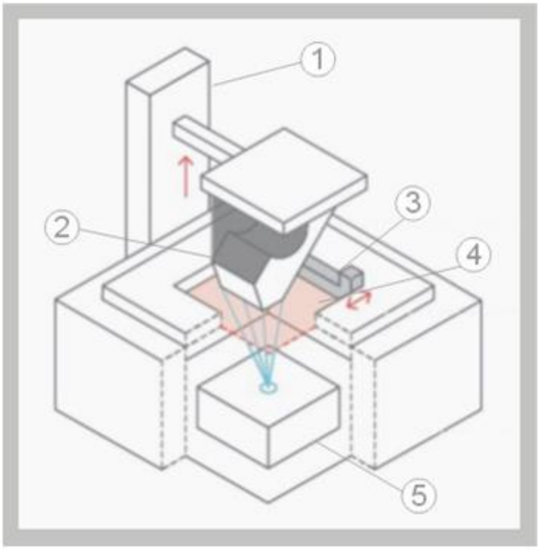

Figure 1.5. Scheme of DLPprinter

1 – Elevator; 2 – Printed part; 3 – Sweeper; 4 – Liquid photopolymer; 5 – DLP projector

The main difference between SLA and DLP technologies is in the type of light source used for resin curing. SLA printers use a dot laser and DLP printers use a voxel approach. In terms of the resolution achieved with each method, standard DMDs have a resolution of 1024x780 pixels, while standard SLA printers use a laser dot with a size of 130-150 micrometers (varies depending on the size of the machine).

The disadvantage of SLA printers is that, compared to DLP printers (that can irradiate the entire cross-sectional area immediately, depending on the size of the printed part), they require more time to trace the cross-section of a part. This makes the DLP printer faster than the SLA when identical parts are printed.

Unlike FFF printers, most parameters of Vat polymerization printers are fixed and cannot be changed. Usually, the only settings that can be specified by the operator are the location of the part and the support, the layer's thickness, and the material. Most printers automatically adjust the settings according to the type of material used. The layer's thickness and the resolution of the light source (the dot size of the dot or the projector's resolution) determine the quality of the surface and the accuracy of the printed part. Most printers of this type produce details with a layer thickness between 25 to 100 micrometers.

Vat polymerization printers can also produce details in two different directions – bottom-up and top-down (Figure 1.6). SLA and DLP printers are available in both configurations, as the design varies depending on the manufacturer.

The bottom-up printers have a light source located under the transparent-bottom resin container. Initially, the build platform is positioned so that there is only one layer of thickness between the base of the tub and the platform. The light source (laser, UV lamp or LED screen) irradiates the thin layer of resin and hardens it. A special coating prevents the resin from sticking to the base of the tub. After the first layer has hardened and gotten stuck to the build platform, the printer performs a separation cycle (stage), separating the dried first layer from the tub's base and moving the platform up with the thickness of the layer. After the separation stage, a new uncured resin layer fills the gap. Some bottom-up printers use a scrubber to distribute the resin layer at the tub' base to provide uniform coverage, mix the resin and remove any residue (hardened resin particles). The process is then repeated, moving the build platform up by the thickness of the layer and separating the newly hardened layer from the tub's base until the completion of the printed part. The bottom-up printers have a non-stick surface applied to the base of the tub to aid the separation phase. It must be changed regularly to ensure adequate performance.

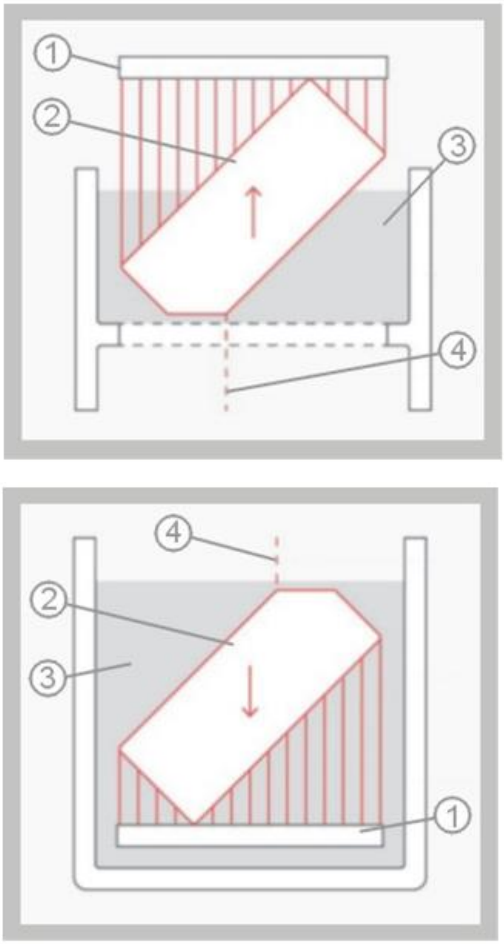

Figure 1.6. Photopolymerization printing from bottom to top and from top to bottom

1 – Build platform moves up/down; 2 – Printed part; 3 – Resin; 4 – Light source

For top-down printers, the light source is located above the build platform. The starting position of the build platform is located on the surface of the resin in the vat and the platform is covered with a thin layer of resin. The light source irradiates the thin layer of resin. After the first layer has hardened, the build platform is moved down by the thickness of one layer, the resin again covers the already hardened layer and the process is repeated. As the printed part is being built, the build platform is continuously descending into the resin tub. Once the printed part tis complete, the latter will be completely immersed in resin. It is then removed from the resin and removed from the build platform. Like with bottom-up printers, the first layer is the most critical in the building process. This layer needs to be successfully attached to the build platform.

For top-down printers, it is important that an even layer of resin covers the work surface after each downward movement of the build platform. To achieve this, it should be ensured that the resins are with appropriate viscosity, which is achieved using patented materials. The build platform should also move slowly in the resin to ensure that no air bubbles are created because they can have a detrimental effect on print quality.

3D printing technology by melting of powdered material

3D printing technology by melting powdered material uses a heat source to induce synthesis between powdered particulates at a specific location in the area of the part that is being printed.

Most powder melting technologies use powder application and smoothing mechanisms as part of the construction, because of which the finished part is sheathed in powder.

3D printing technology by melting of powdered polymeric material (Selective Laser Sintering - SLS)

The use of Powder Bed Fusion technology with polymer powder to produce parts is commonly referred to as selective laser sintering (SLS) or simple laser sintering (LS). The SLS process starts by heating a container of polymer powder to a temperature just below the melting point of the polymer. A recoater deposits a very thin layer of powdered material (usually 0.1 mm) on the build platform. Then a CO_2 laser beam starts scanning the surface. The laser selectively agglomerates the polymer powder and hardens it along the cross section of the part. Similarly to the SLA method, the laser is focused on the correct place by a pair of galvanometers. When the entire cross-section is scanned, the build platform moves down along the height by a thickness of one layer. The recoater then applies a new layer of powdered polymer to the top of the recently processed layer and the laser starts to sinter the next cross-sectional portion of the part onto the previously hardened one. This process is repeated until the printed part is finished. The unmelted powder remains in place to support the part during its building. This eliminates the need for supporting structures. This is one of the main advantages of SLS technology. Figure 1.7 shows a scheme of a SLS printer.

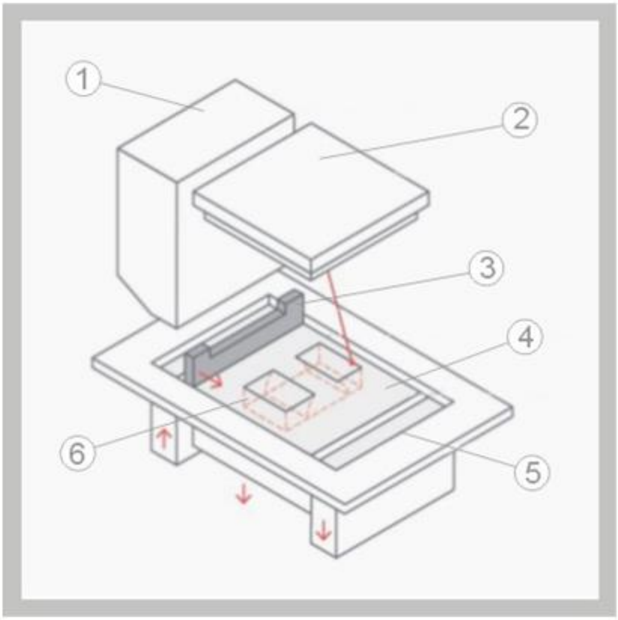

Figure 1.7. Scheme of a SLS printer

1 – Powder feeder; 2 – Laser scan system with heaters 3 – Recoater; 4 – Build platform; 5 –Overflow bin; 6 – Printed part

When the printing process is complete and the bin with powder and parts has cooled, the bin is unpacked. Solid products are separated from the unmelted powder and cleaned with compressed air and blasting with abrasive material. About 50% of the unmelted powder is collected and reused. The parts are then ready for use or further processed to improve their appearance. Figure 1.8 shows the SLS printing process.

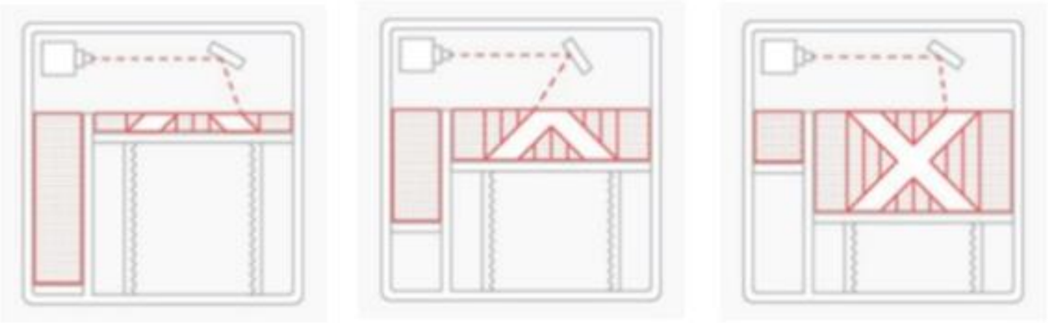

Figure 1.8. SLS printing process

There is a set of parameters that determine the print quality of the SLS printer. The accuracy and quality of the product's surface are determined by the size of the laser spot and the thickness of the layer. Most SLS parts are printed with a standard layer height of 100 micrometers (0.1 mm).

The geometry and size of the powder particulates also play an important role on the properties of the final product. Finer powders lead to a smoother surface of the printed part but create problems with transport and dispersion during the coating of the new layer. Coarser powders, although easier to work with, have an adverse effect on the quality of the surface and the permissible dimensions of the elements.

The optimal settings of the device are usually set by the printer manufacturer. The printers automatically adjust their parameters depending on the materials used by the operator. SLS printers are autonomous during the heating, printing and cooling phases. Operator involvement is only required for loading and unloading containers and for monitoring the printing.

As all other 3D printing methods, SLS creates the parts layer by layer. Adhesion between the layers is important to achieve the product's desired reliability and strength. The preheating of the printing powder, followed by the action of the sintering laser, causes the particles to adhere to each other in different directions. As a result, homogeneous products are obtained.

3D printing technology by melting of powdered metal material (Direct Metal Laser Sintering - DMLS; Selective Laser Melting - SLM; Electron Beam Melting - EBM)

In 3D printing by melting of powdered metal material, a heat source causes the synthesis of powdered particulates in the layer. Variations in this technology involve the use of different energy sources - lasers or electron beams.

Both Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM) produce parts by a method similar to SLS. The main difference is that DMLS and SLM are used in the production of metal parts. DMLS does not melt metal powder but heats it to such an extent that particulates can bind at the molecular level. SLM uses the laser to completely melt the metal powder and to form a homogeneous product. Thus, the printed parts have one melting point. This is the main difference between DMLS and SLM: the first technology makes parts from metal alloys, and the second - from single-element metals. Figure 1.9 shows the schematic representation of the DMLS / SLM printer.

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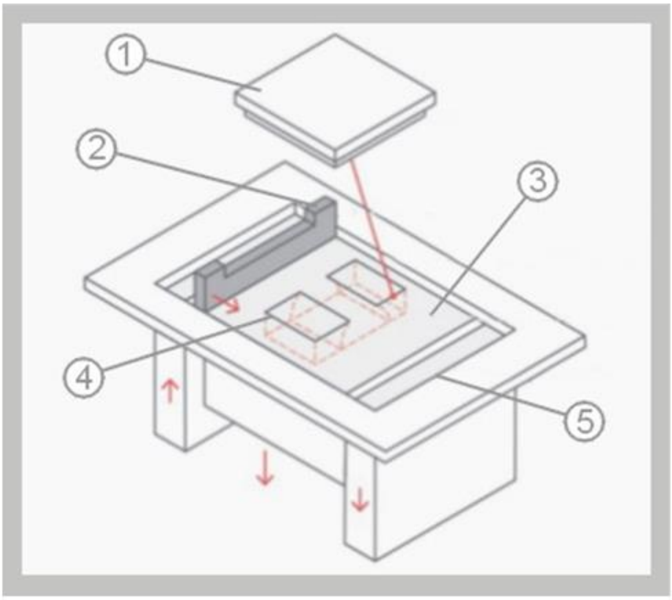

Figure 1.9. Scheme of DMLS/SLMprinter

1 – Laser scan system with heaters; 2 – Recoater; 3 – Build platform; 4 – Printed part; 5 – Overflow bin

As opposed to the SLS process, DMLS and SLM processes require structural support of the printed part to prevent eventual distortions that may occur, even though the surrounding powder provides support. DMLS/SLM parts are at risk of distortion as a result of residual stresses occurring during printing due to high processing temperatures. After printing, the parts are heat-treated while they are still attached to the build platform to relieve any stresses on them. Figure 1.10 shows the DMLS/SLM printing process.

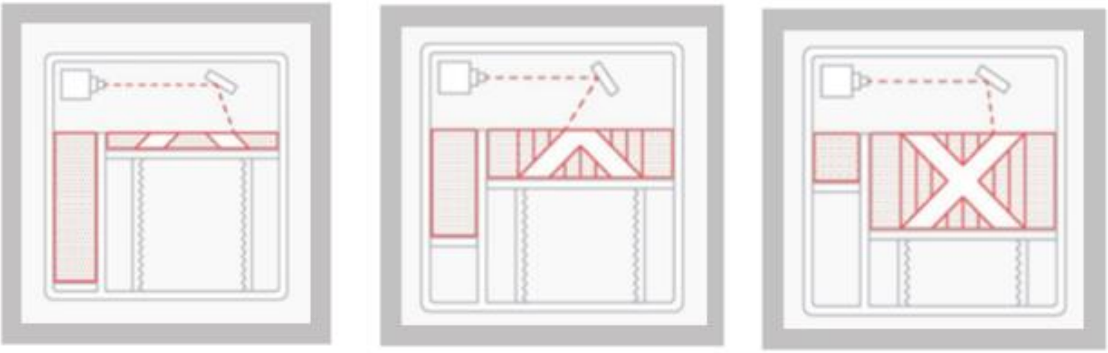

Fig 1.10. The DMLS/SLM printing process

Similarly to SLS, the accuracy and surface quality of parts printed by DMLS/SLM are determined by the size of the laser spot, the geometry of the powder and the layer thickness. Metal additive production systems cannot be integrated automatically; they need highly qualified operators.

In contrast to other powder melting technologies, Electron Beam Melting (EBM) uses a high-energy beam (electrons) instead of a laser (photons) to cause bonding between metal powder particulates. The focused electron beam processes a thin layer of powder, causing local melting and hardening over a certain cross-sectional area.

Compared to DMLS and SLM, EBM has a higher build speed due to higher energy density. EBM printed parts are made under vacuum and the process can only be used with conductive materials.

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3D printing technology through 3D inkjet printing (Material Jetting - MJ; Drop on Demand - DOD)

This technology builds the printed parts layer by layer using photopolymers or wax droplets, which harden under the influence of light. The nature of the inkjet 3D printing process allows different materials to be applied to the same product. This is used to print support beds of different materials.

The 3D Material Jetting (MJ) works similarly to a standard inkjet printer, but instead of printing one layer of ink, it prints many layers on top of each other to create the entire product. The print head of the printer injects hundreds of small photopolymer droplets and irradiates them with ultraviolet (UV) light. After the layer is deposited and hardened, the build platform is lowered by the thickness of one layer and the process is repeated until the whole part is built.

Unlike most 3D printing technologies, which deposit, harden or sinter the printing material using point deposition technology (one point follows a route to cover the entire cross-sectional area), Material Jetting operations deposit the printing material quickly, along lines (Figure 1.11). Therefore, this type of printer can print multiple details in a row. If the details are placed correctly and the work in each construction line is optimized, then Material Jetting 3D printing is able to produce products at a much faster rate than other 3D printing technologies.

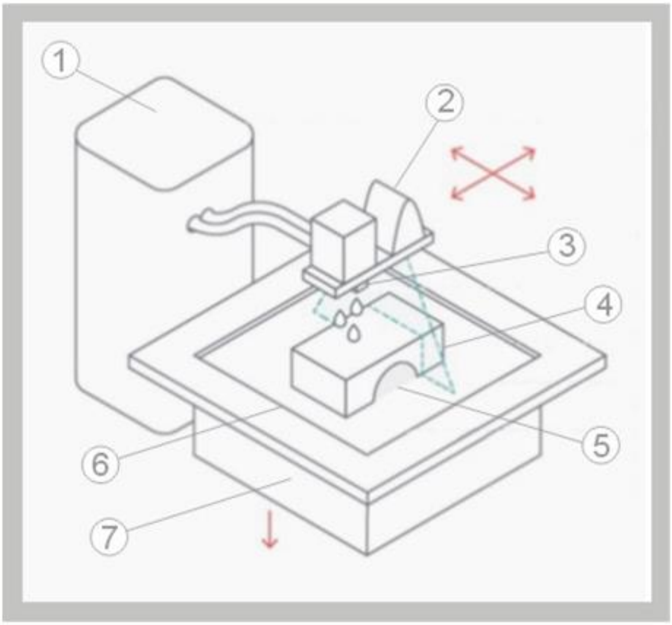

Figure 1.11. Scheme of 3D Material jetting printer

1 – Material container; 2 – UV curing light; 3 – Inkjet print heads; 4 – Printed part; 5 – Support material; 6 – Build platform 7 – Elevator

The Material Jetting 3D printing requires a support bed, which is printed simultaneously with the part and is removed during post-processing. This technology allows the simultaneous use of multiple materials and full colour printing. Figure 1.12 shows the Material Jetting 3D printing process.

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Figure 1.12. Material Jetting 3D printing process

Drop On Demand (DOD) printers use two print heads: one for deposition of the print material (usually wax material) and the other for the soluble material of the support bed. The DOD printer follows a specific route and jet material at a single moving point for layering the material along the cross-section of the printed part (as opposed to the MJ technology, in which the material is deposited in a single line). The DOD printer also uses a fly-cutter, which removes a thin layer from the work area after each layer has been made, to ensure a perfectly flat surface before printing the next layer. DOD technology is commonly used to produce wax templates under wax molding.

The Material Jetting 3D printers inject the printing material or support material to create the product. The size of the droplets in the jet (directly related to the diameter of the print-head nozzle) and the thickness of the layer affect the quality of the surface and the size of the smallest elements of the product. Material Jetting 3D printing is one of the most accurate 3D printing methods, capable of producing details with a layer height of up to 16 micrometers and very smooth surfaces. Maintaining the print head is important to limit clogging or blockage due to the small nozzle diameters. Printers usually have nozzle cleaning systems or send notifications to the operators if cleaning is required.

It is also important that the printing material be liquid in order to be successfully injected onto the work area. Most printers heat the resin to the optimum temperature (30° C to 60° C) to control the viscosity of the photopolymer during printing. These printers automatically adjust their parameters based on the material that is used.

One of the biggest advantages of the Material Jetting 3D printers is the ability to print with two different materials - a basic one, and one for the soluble support bed. This means that, unlike other 3D printing methods, in which the support bed is manually detached from the printed part, in these printers it is dissolved and removed easily. In this way a surface can be obtained without any traces of supporting bed.

Material Jetting 3D printing allows for printing parts with matte or glossy surfaces. To obtain a matte surface, the printer deposits a thin layer of the support bed's material along the entire part. Where a glossy surface is needed, the supporting material is used only where it is necessary.

Material Jetting 3D printing is considered the most accurate type of 3D printing. Because there is no heat involved in the printing process (other than initially heating the resin to an ideal printing temperature), distortion and shrinkage are atypical for this technology. Decreased printing accuracy is manifested by increasing the size of the product, due to shrinkage of the photopolymer during curing.

3D printing technology through Binder Jetting (Binder Jetting - BJ)

Binder Jetting printing is a universal 3D printing technology with different applications. This is the process of deposition of binder on a powdered layer during the shaping of the part. The layers are stuck to each other and so the whole product is obtained. Binder Jetting exists in two versions: sand printing and metal printing.

Printing under this technology is similar to SLS, except that an initial layer of powder is needed on the build platform. Unlike SLS technology, which uses a powder sintering laser, this technology moves the print head over the surface of the powder, depositing the binder's droplets (80 micrometers in diameter) that bind the powdered particulates together to create every part's layer. After the printing of the layer is completed, the build platform is lowered, and a new layer of powder is deposited on the already printed layer. This process is repeated until the complete shaping of the printed part. The product is then left in the powder to harden and gain strength. Finally, it is removed from the powdered layer and the unbound powder is removed by compressed air.

Sand printing is a cheap method of making sand products (known as sandstone or gypsum). The most common methods of sand printing are:

- *Full colour models*: Gypsum or PMMA (polymethyl methacrylate) powders, together with a binder liquid, are used for the full colour printing of products. The print head injects the binder and the auxiliary print head injects ink, which allows full colour products to be printed. Once the products are completely hardened, they are removed from the loose unbound powder and cleaned.
- *Sand molds and casting cores*: After printing, the sand molds and cores are removed from the printing chamber and cleaned to remove the remaining sand. Then the molds are usually ready for casting. The main advantage of sand molds and casting cores produced in this way is the relatively low cost and the complex geometry that can be realized. The process can be integrated into an existing production or foundry process without special requirements.

Figure 1.13 shows the scheme of a Binder Jetting 3D printer, and in Figure 1.14 a Binder Jetting 3D process is shown.

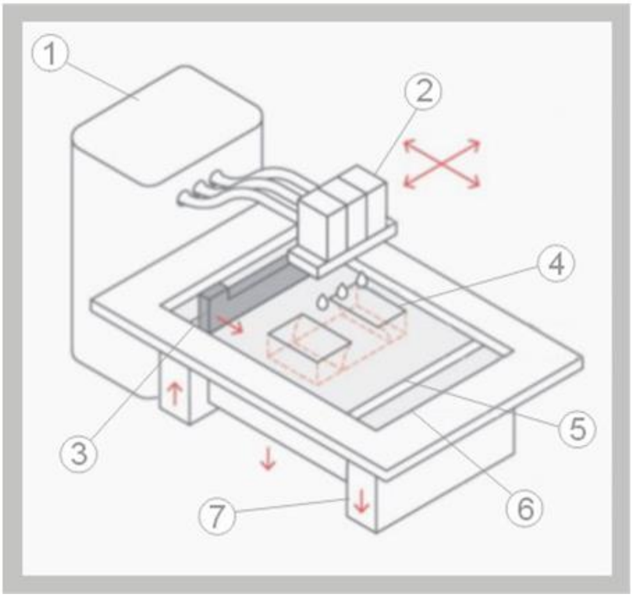

Figure 1.13. Scheme of a Binder Jetting 3D printer

1 – Material container; 2 – Inkjet print heads; 3 – Re-coater; 4 – Printed part; 5 – Powder bed; 6 – Build platform; 7 – Overflow bin

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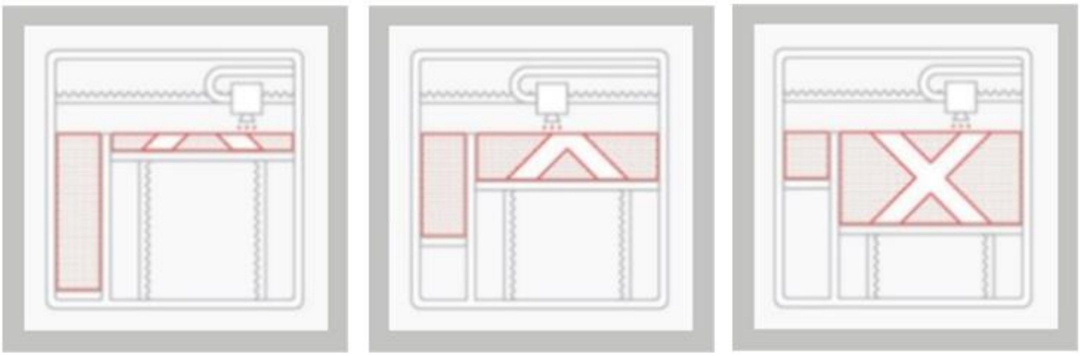

Figure 1.14. 3D Binder Jetting process

Binder Jetting printing is also used for the manufacturing of metal products. The metal powder is bonded by a polymer binder. The production of metal products with the help of this technology allows the manufacturing of parts with complex geometry that cannot be realized by traditional production technologies.

Initially, the metal powdered particulates are bonded together with the binder to obtain the intermediate state of the part. Once the parts are completely hardened, they are removed from the bulk powder and placed in an oven, where the binder burns, leaving pores in the product (density about 60%). Bronze is then used to fill the pores, resulting in high density (greater than 90%) and good strength of the part.

Metal parts can also be produced by a secondary sintering process. Once the intermediate state of the product has been obtained, it is cured in a temperature chamber. It is then sintered in a furnace obtaining high density (more than 97%).

The part's accuracy and surface quality depend on the layer height, droplet size, powder size and geometry. Similarly to SLS technology, Binder Jetting printing does not require the printing of support beds, as the products are surrounded by powder during the printing process. This reduces post-processing time and the amount of printing material consumed.

One of the limitations of Binder Jetting printing is the products' strength. Even after secondary treatment, the parts have limited strength compared to parts obtained by melting powder material. Such parts are usually used as functional parts after secondary technological processes (except for parts produced by sand casting).

Full-colour sand products are printed with a layer thickness of 100 micrometers, and sand molds and casting cores - with a layer thickness of 249 up to 380 micrometers. Some printers are able to print 50 micrometer layers if a smooth surface is required. This increases the cost and printing time. Products using this technology are printed without the application of high temperatures. This avoids complications associated with uneven cooling that can lead to distortions and deformations.

3D printing technology through Laser Metal Deposition – LMD

Laser Metal Deposition (LMD) is also known as Direct Metal Deposition (DMD), Direct Energy Deposition (DED) or Laser Engineered Net Shaping (LENS). The technology was proposed for the first time by Sandia National Laboratory in the 1990s. In this case, the part is locally heated by a laser beam, creating a melting pool on its surface. Fine metal powder is automatically added to the melting pool via a nozzle (p-LMD). Except via a nozzle, the deposited material can also be fed to the melting pool via a metal wire (w-LMD). There it melts and combines with the base material to form a layer 0.2 to 1 millimeter thick. A metallurgical bond is created between the layer and the base material. If required, numerous layers can be built upon each other (Figure 1.15). Argon is often used as the shielding gas. Shielding gas is used to prevent the oxidation of metals when heated with a laser beam. An automatically controlled optical system is used to direct the laser beam along a specified shape. An intelligent sensor system ensures that the layer thickness is even everywhere and at all times. The process continues until the part is covered with a metal layer or the appropriate amount of coating is reached during repair.

Figure 1.16 shows different examples of LMD-based technologies, all of which perform the same basic process of applying metal powder / wire to a base material in a layer-by-layer process.

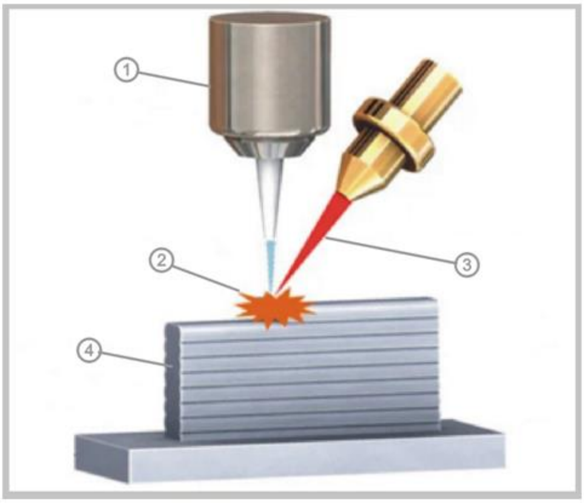

Figure 1.15. Scheme of Laser Metal deposition (LMD)

1 – Powder feeder; 2 – Melting pool; 3 – Laser beam; 4 – Thin wall deposit

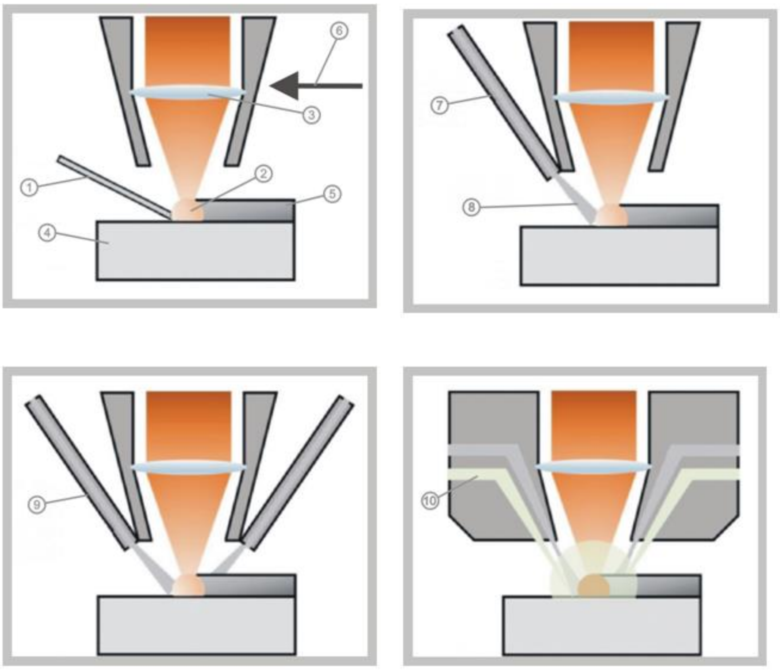

Figure 1.16. Functional diagrams of different types of machines for Laser Metal Deposition (LMD)

1 – Wire; 2 – Melting pool 3 – Lens; 4 – Base material; 5 – Deposited material; 6 – Direction of movement; 7 – Lateral injection nozzle; 8 – Powder stream; 9 – Radially symmetric injection nozzles; 10 – Shield gas

LMD is a technological process that can be used outside of additive manufacturing. In most cases, the LMD laser and the nozzle are limited along the Z axis while the part is moving in the X-Y plane. However, the compact nature of the LMD allows it to be included in robotic arms, giving it many more levels of freedom. These robotic LMD devices are ideal for repairing existing components, as the laser and nozzle can travel freely around existing structures. The LMD process can also be adapted by varying the laser power, melting pool width, speed of movement, speed of powder supply, material composition and other.

Laser metal deposition is a unique technology that allows for the manufacturing of high-precision components. Due to the cost of specialized raw powder materials and laser equipment with protective atmosphere, in many cases the technology is considered expensive. Therefore, LMD is mostly applied in high value-added production. LMD is a very precise and a very fast method and allows the creation of both coarse and very fine structures. The range of materials suited for LMD is wide, including one-component metal powders, tungsten carbides, powder alloys and even custom powder mixtures to create sandwich-like bimodal structures or new alloys. There is also minimal waste of material because material is added only when needed. LMD is effective in the production, repair, welding and coating, making it a multifunctional manufacturing process.

The capital costs for the LMD process equipment are very high. The cost of materials is also high. The process requires high quality metals with low pollution and powder that does not clog the nozzles when spraying. The process is very complex and requires trained operators to set up LMD machines. The bimodal nature of the microstructure can become a problem, especially if the laser is not properly adjusted. Surface coatings can be rough and porous.

The main applications of LMD technology are related to repair of tool surfaces, engine components, turbine blades, etc.; development of new alloys; medical implants; rapid prototyping; production of details for aerospace, oil and gas energy and many others.

3D printing technology through Laminated Object Manufacturing - LOM; Selective Deposition Lamination - SDL; Ultrasonic Additive Manufacturing - UAM

The building of parts via the Laminated Object Manufacturing (LOM) method is a rapid prototyping technology developed by Helisys Inc. (the successor of Helisys Inc. is now Cubic Technologies). This method is based on layers of sheet material (paper, plastic, or metal laminates) that are successively glued together and cut to shape with laser cutter. Objects printed with this technique may be additionally modified by machining after printing. The thickness of the applied layer depends on the thickness of the sheet material used.

The printing process proceeds as follows (Figure 1.17). A sheet of adhesive-coated material is deposited on the moving platform (or on the bottom layer of the printed part) using a heated roll. The layer's shape is drawn with the help of a laser. Excess material is cut by the laser into small sections to facilitate its removal. The platform with the finished layer is moved down. A new sheet of material is fed into the working chamber. The moving platform is raised to contact with the new material. The cycle is repeated until the product is finished, after which the excess material is removed and a final machining (drilling, grinding, etc.) is performed.

Paper-based printing products, after completing the manufacturing process, resemble wood and can be processed accordingly. They are often covered with varnish to be protected against moisture.

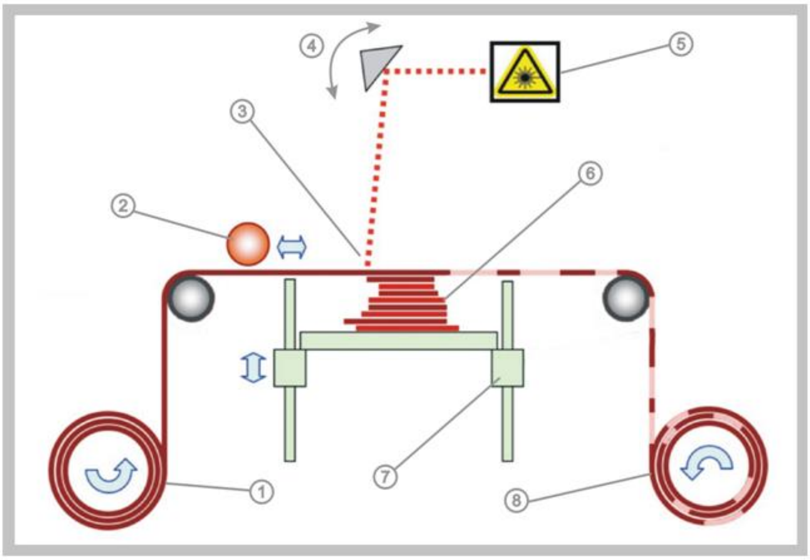

Figure 1.17. Laminated Object Manufacturing process

1 – Foil roll; 2 – Heated roll; 3 – Laser beam; 4 – Mirror; 5 – Laser; 6 – Layers; 7 – Moving platform; 8 – Waste

The method stands out for its low cost, which is due to the use of commonly available materials. The printing accuracy is lower than that of stereolithography (SLA) and selective laser sintering (SLS) but the technology is simpler. Large-size products can be made using this technology.

Selective Deposition Lamination (SDL) is a 3D printing process using paper. This process is similar to the LOM rapid prototyping method. In the SDL method only parts of the sheet that builds the product are glued, while in LOM the whole sheet is glued evenly.

In SDL technology, the product shape is pre-cut on the sheet and the glue is applied only on the part that needs to be glued. Because the adhesive is applied selectively, this method is called "selective". The adhesive material is applied with a higher density to those areas that will become part of the product and with a lower density - to those areas that will serve as support of the printed part.

Ultrasonic Additive Manufacturing (UAM) or Ultrasonic Consolidation (UC) constitutes a method for low-temperature 3D printing of metals. The technological process was invented and patented by Dawn White. In 1999, White founded the company Solidica Inc. specialized in UAM equipment. In 2011, the company Fabrisonic LLC was established, which offers machines based on an advanced UAM process – Sonic Layer (ultrasonic welding of metals).

The technological process is as follows (Figure 1.18). A base metal substrate is placed on a machine anvil and fixed on it. The metal foil is then pulled under the sonotrode, which applies pressure to the foil and connects it to the metal substrate by ultrasonic vibration. High-frequency ultrasonic vibrations are applied topically to metal foils placed together under pressure to create a weld. The vibrations of the transducer are transmitted to the disk-shaped welding sonotrode, which in turn creates an ultrasonic weld between the thin metal foil and the substrate. This process is repeated until the required area is covered with ultrasonically sealed material.

After reaching a thickness of 3-6 millimeters, a CNC machine is used to cut the excess foil from the product and achieve the required geometry. The deposit and trimming cycle continues until the product is manufactured. It is then removed from the anvil and taken out of the metal substrate.

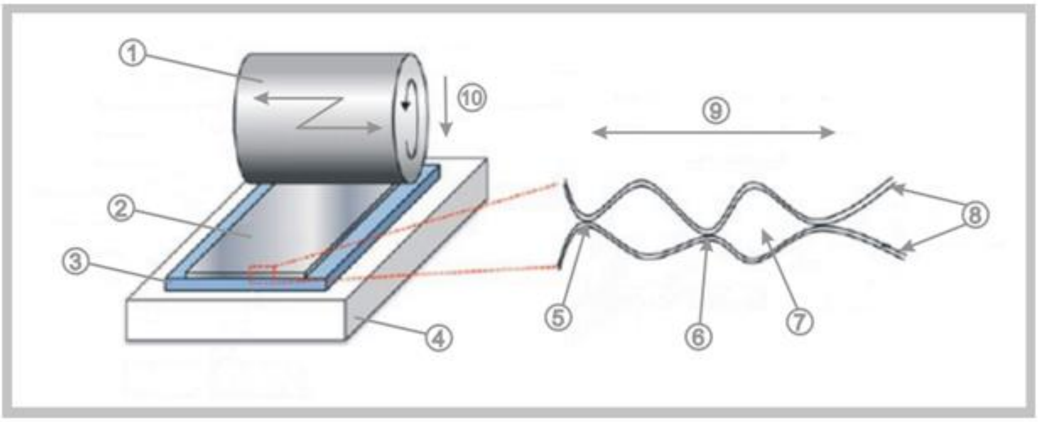

Figure 1.18. Scheme of the UAM technological process

1 – Rotating sonotrode; 2 – Foil to be welded; 3 – Metal substrate; 4 – Anvil; 5 –Surface points; 6 – Contact; 7 – Void; 8 – Oxide layer; 9 – Ultrasonic oscillation; 10 – Normal force

Ultrasonic metal welding has existed since the 1950s and has been applied for welding battery plates, thin film packaging and more. The ultrasonic welding operation begins by pressing a thin metal foil onto another metal component. While under constant force, ultrasonic vibrations are applied to cause cleaning of the surface oxides through friction. Thus, direct contact of pure metal with pure metal is achieved. As a result, a solid atomic bond is formed with minimal heating. Thermal and plastic deformations support the diffusion and recrystallization of the boundary, leading to a true metallurgical bond. Ultrasonic welding can be performed at very low temperatures and without the need to ensure a special environment. For all metals, the bonding temperature is significantly below their respective melting temperature.

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Materials used in 3D printing

The materials used in 3D printing are determined by the technology. Each 3D printing technology converts the material through externally applied heat, light or other types of directed energy. When choosing a material for the 3D printing of a particular product, it is necessary to ensure that the material meets the relevant requirements. Some materials offer biocompatibility, certificates for skin contact, certificates for lack of smoke toxicity, for non-flammability, for chemical resistance, etc. When choosing a material and technology for 3D printing, the requirements for dimensional accuracy, minimum execution time and the walls thickness of the structure should be considered.

3D printing materials are subjected to rigorous testing of all types of stresses to which they can be subjected, and of the environmental impact in which the material will be used. The ability of the material to function well in the conditions created by its desired application depends in part on the design of the part.

Some of the most important properties when choosing materials for 3D printing are tensile strength, resistance to bending and tearing (flexural strength), resistance to bending under load (flexural modulus), elongation, impact strength, compressibility, water adsorption, heat deflection temperature (HDT), Vicat softening temperature, coefficient of thermal expansion, etc.

Tensile strength is the resistance of the material to tearing under stress and is one of the fundamental properties of a material.

Young's modulus is a measure of the material's hardness under tensile load - the higher its value, the harder the material.

Flexural (bending) strength describes the resistance of the material to breakage under load. The difference between bending strength and tensile strength is in the type of load. For most plastics, the values of bending and tensile strength are very close - in fact, if the material is isotropic, its bending strength would be equal to the tensile strength.

The flexural (bending) modulus is a metric of the material stiffness in the direction of bending. A high value of bending modulus is a sign of a harder material. Just like tensile and bending strengths, tensile and bending moduli are closely related and usually do not differ much.

Hardness is defined as the resistance of a material to a change in its constant shape when a compressive force is applied. To determine it, the Shore method (Shore hardness scale) is used - a method of testing and definition designed to measure the hardness (or softness) of soft, flexible and elastic materials such as rubber, elastomers and some polymers. High Shore hardness means a harder and less flexible material.

Water adsorption: when heated above a certain temperature threshold - usually around 150-160°C - in the presence of moisture many thermoplastic materials undergo a chemical reaction called hydrolysis, which breaks long molecular chains into shorter ones and weakens the material. If a thermoplastic raw material with a high adsorption capacity is exposed to moisture before 3D printing, hydrolysis takes place, which leads to deteriorating quality of the final part.

The Heat deflection temperature (HDT) represents the temperature at which the material begins to deflect under a specific load.

The Vicat softening point reflects the change in the mechanical properties of the material under the influence of heat. It is usually used to determine the upper temperature limit for continuous use of a material in applications with elevated operating temperatures. Operating temperatures should normally be 15°C below the Vikat softening point.

The coefficient of thermal expansion is a useful indicator for predicting and quantifying the way in which the material will change its shape due to changes in temperature. A positive coefficient of thermal expansion indicates that the material will expand when temperature increases. When working with thermoplastic materials, the thermal expansion of the material should be considered in order to obtain the desired shape after the part has cooled.

3D printing materials can be divided into three groups: polymers, metals and other materials (Figure 2.1).

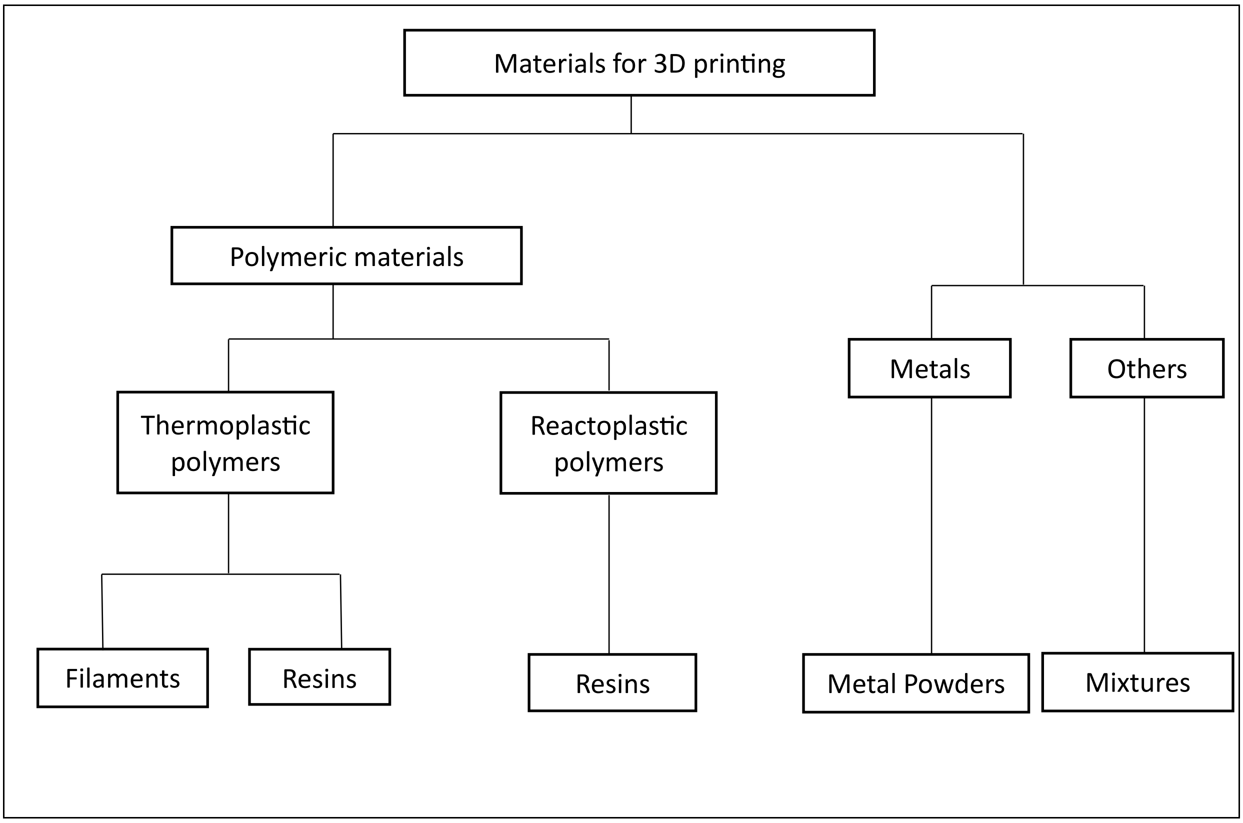

Figure 2.1. Types of materials for 3D printing

Polymeric materials

In 3D printing, polymers are used in different forms: plastic filament (wire), resin and powder. They are divided into two types: thermoplastic and reactoplastic polymers. The two types differ in their behaviour when exposed to external influences.

Thermoplastic polymers

Thermoplastic polymers can melt and harden repeatedly while retaining their properties. In the process of FFF printing, thermoplastics are used as they are heated to a plastic state and extruded on a build platform, where they are then hardened.

In FFF printing, thermoplastic materials are used in the shape of filament spools, usually 1.75 mm or 3 mm in diameter. They are one of the cheapest materials used in 3D printing. The filaments are available in a wide range of colours (Figure 2.2). The better the engineering properties of the material, the higher the temperature required to heat to a plastic state, and thus more difficult to print. Higher temperatures increase the probability of deflections or deformation during the printing process as the printed parts cool down at an increased rate, leading to more intense internal stresses.

The thermoplastic materials range is very large. The main thermoplastic polymers are:

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- **Polylactide (PLA)**

Polylactide is one of the most widely used thermoplastic polymers. This is due to several factors. PLA is an environmentally friendly material. It is a polymer of lactic acid and is completely biodegradable. Corn and sugar cane are used for its production. At the same time, its environmental friendliness determines its short life. As a rule, details from PLA are not intended for functional use, but serve as designer models, souvenirs and toys. Among the few practical industrial applications are the production of food packaging, drug containers and surgical sutures. It is characterized by a low melting point (170-180°C), which contributes to low power consumption and the use of nozzles made of brass and aluminium. Extrusion is performed at 160-170°C. At the same time, the PLA hardens slowly enough, which should be considered when choosing a 3D printer. PLA has low compressibility (loss of volume during cooling), which prevents deformation. The price of PLA is not high. Famous brands of PLA are: ColorFab, Formfutura, Innofil, Polymaker, Ultimaker.

Fig.2.2. Filaments used in 3D printing

- **Acrylonitrile butadiene styrene (ABS)**

ABS is the most famous thermoplastic used for 3D printing, but not the most common. This contradiction is related to certain technical difficulties that arise when printing with ABS. The use of ABS is determined by its excellent mechanical properties, durability and low cost. In the industry it has found wide application in the manufacturing of automotive parts, housings of various devices, souvenirs, household accessories and more. ABS is resistant to moisture, acids and oil. Some ABS types are destroyed under the influence of direct sunlight, but at the same time ABS is easy to paint, which allows a protective coating to be applied. Due to the amorphousness of the material, ABS has no melting point, but the acceptable extrusion temperature is considered 180°C, which is comparable to that of PLA. The main disadvantage of ABS is the high degree of shrinkage during cooling (it can lose up to 0.8% of its volume). This can lead to significant deformation of the parts. Two main solutions are used to counteract this. First, preheated build platforms are used to reduce the temperature gradient between the lower and upper layers of the printed parts. And second, 3D printers with ABS often use closed enclosures and perform background temperature control in the work chamber. This keeps the temperature of the deposited layers slightly lower than the curing threshold, reducing the degree of shrinkage. Complete cooling is performed after receiving the finished part. The relatively low "stickiness" of ABS may require additional means of attachment to the work surface, such as adhesive tape or applying a solution of ABS in acetone on the build platform immediately before printing. At room temperature, ABS do not endanger health. However, when heated, it releases acrylonitrile vapours (a poisonous compound that causes mucosal irritation and poisoning). Although the acrylonitrile released during printing is insignificant, it is recommended that printing be carried out in well-ventilated premises or ventilation be provided. The good solubility of ABS in acetone is very useful as it allows large parts to be produced with subsequent gluing. Famous brands of ABS are: Esun, Stratasys, Ultimake.

- **Polyvinyl alcohol (PVA)**

Polyvinyl alcohol is a material with unique properties. The main feature of PVA is its water solubility. 3D printers equipped with dual extruders have the ability to print the part with PVA support beds. After finishing the printing, the substrate can be dissolved in water and so the finished printed part does not require additional processing. PVA can be used to create water-soluble master models for foundry molds and the foundry molds themselves. The mechanical properties of PVA are also interesting. At low humidity it has a high tensile strength. As the humidity increases, the strength decreases, but the elasticity increases. The extrusion temperature is 160-175°C, which allows the use of PVA in printers designed for printing with ABS and PLA. Temperature above 220°C leads to PVA decomposition, which should be considered when printing.

- **Nylon**

Nylon is attractive with its high wear resistance and low friction coefficient. There are several types of nylon that differ in their characteristics. The most famous is nylon-66, developed by DuPont in 1935. The other most famous is nylon-6, developed by BASF. These two types are similar. From the point of view of 3D printing, the main difference is in the melting temperature - nylon-6 melts at 220°C, and nylon-66 at 265°C. As nylon easily absorbs moisture, 3D printing material should be stored in a vacuum pack or in a container with moisture-absorbing materials. A sign of excessive moisture is the steam coming out of the nozzle during printing. This can reduce the quality of the printed part. As toxic fumes can be released when heating the nylon, it is recommended that 3D printing be performed in well-ventilated premises or ventilation be ensured. Famous brands of Nylon are: Stratasys, Taulman3D, Ultimaker.

- **Polycarbonate (PC)**

Polycarbonate is characterized by high strength and resistance to high and low temperatures. The extrusion temperature depends on the printing speed, but the minimum temperature at a speed of 30 mm/sec can be considered 265°C. When printing, it is recommended to use polyimide tape for a good grip on the surface of the build platform. The tendency of PC to deformation requires the use of a preheated build platform and, if possible, a closed housing with a preheating of the working chamber. It is recommended that the printing process be carried out in well-ventilated premises due to the possibility to release the carcinogenic compound bisphenol during heating. PC has high hygroscopicity, which is why it is necessary to store the printing material in dry conditions to avoid bubbles in the deposited layers.

- **High density polyethylene (HDPE)**

The world's most widespread plastic polymer – polyethylene - is not commonly used as 3D printing material. The reason for this is the complexity of layer-by-layer preparation of the parts. Polyethylene melts easily at 130-145°C and hardens quickly at 100-120°C, because of which the deposited layers often fail to adhere. In addition, it is characterized by high compressibility and deformation of the part due to uneven cooling. 3D printing with polyethylene requires the use of a preheated platform and a working chamber with precise temperature adjustment to slow down the cooling of the deposited layers. In addition, printing has to be performed at high speed. The melting of polyethylene emits vapours of harmful substances, which is why it is recommended that printing be performed in well-ventilated premises.

- **Polypropylene (PP)**

Polypropylene is non-toxic, has good chemical resistance, resistance to moisture and is cheap. A shortcoming of this material is that it changes its properties at temperatures below -5°C and under direct exposure to sunlight. The main difficulty in printing with polypropylene, however, is its high compressibility during cooling (up to 2.4%). Although polypropylene adheres well to a cool surface, it is recommended that printing be performed on a preheated build platform to avoid deformation of the printed part. The minimum extrusion temperature is 220°C. Polypropylene fibres for printing are offered by the companies Orbi-Tech, German RepRap, Qingdao TSD Plastic. The company Stratasys has developed a polypropylene imitation product called Endur, which is optimized for 3D printing.

- **Polycaprolactone (PCL)**

Polycaprolactone (Hand Moldable Plastic, Mold-Your-Own Grips, InstaMorph, Shapelock, Friendly Plastic, Polymorph) is a biodegradable polyester characterized by a very low melting point (about 60°C). This feature creates certain problems with 3D printing, as not all 3D printers can be set to operate at such low temperatures. Heating polycaprolactone to the extruder temperatures typically used (about 200°C) causes loss of mechanical properties and can damage the extruder. PCL is non-toxic and safe as the material degrades in case of ingestion. Polycaprolactone is not very suitable for creating functional mechanical parts, but it is a material very suitable for the production of mock-ups. It adheres easily to the surface of even a cool build platform and is easily coloured.

- **Polyphenylsulfone (PPSU)**

Polyphenylsulfone is a high-strength thermoplastic used in the aviation industry. The material has very good chemical and heat resistance, and practically does not burn. PPSU is biologically inert. Its operating temperature range is from -50 °C to 180 °C. It is resistant to solvents, fuels, and lubricants. Despite all these advantages, PPSU is not used very often in 3D printing as it has a high melting point (370°C). Such an extrusion temperature is beyond the capabilities of most desktop printers. The only active user of the material is the company Stratasys, which offers the Fortus industrial facility.

- **Polymethyl methacrylate (Acrylic)**

Polymethyl methacrylate is a material that is characterized by strength and moisture resistance. It is environmentally friendly, sticks easily, is sufficiently plastic and is resistant to direct sunlight. For several reasons, however, it is not suitable for 3D printing by extrusion. Polymethyl methacrylate is not easily stored in the form of a filament spool, as constant mechanical stress leads to the gradual destruction of the material. Its fast curing requires precise climate control in the working chamber and high printing speed. Nevertheless, technology companies are seeking opportunities for printing with it. The best results were achieved with the technology of 3D inkjet printing of the company 3D Systems, which uses a photopolymer version of polymethyl methacrylate. Success has also been achieved by the company Stratasys, which uses its own photopolymer simulator of polymethyl methacrylate VeroClear on Objet Eden printers.

- **Polyethylene terephthalate (PET)**

This material is used to produce plastic bottles and packaging for food and medical products. It has high chemical resistance to acids, bases, and organic solvents. It has high wear resistance and stability in a wide temperature range (from - 40°C to +75°C). Polyethylene terephthalate is easily machinable. What is special about 3D printing using PET is its relatively high melting point, up to 260°C and significant shrinkage when cooled (up to 2%). For this reason, the same conditions as for printing with ABS thermoplastic should be applied. Transparency of the part can be achieved with rapid cooling when the curing threshold is exceeded (70°C – 80°C).

- **High Impact Polystyrene (polystyrene) (HIPS)**

It is widely used in the industry to produce various household products, construction materials, toys, medical instruments, etc. In 3D printing, HIPS has physical properties similar to those of ABS thermoplastics. Polystyrene differs from ABS in its chemical properties. It is easily dissolved by the organic solvent Limonene. As this solvent does not affect ABS, it is possible to use polystyrene as a material for soluble supporting structures. This is very useful when building complex parts with internal supports. Compared to water-soluble polyvinyl alcohol, polystyrene has a relatively low cost and resistance to humid environments. Toxic fumes may be released when HIPS is heated to extrusion temperature. In this regard, it is necessary that the printing process be performed in well-ventilated premises.

Reactoplastic polymers

Unlike thermoplastic polymers, reactoplastic polymers do not melt. Initially, they are a liquid with a high viscosity and then they harden. Curing can be performed by exposure to heat, light or after mixing with a catalyst (hardener). After curing, the reactoplastic polymers cannot melt. Under the influence of high temperatures, they lose their structural integrity. SLA/DLP processes and 3D inkjet printing use photo polymeric reactoplastic polymers (resins) that harden when exposed to a laser beam or ultraviolet light.

Unlike thermoplastic polymers, reactoplastics are designed for a specific 3D printer. Their development is carried out by printer manufacturers. The reason for this is both the technological features of specific printers (lighting time, print speed, etc.) and the purpose of the finished products. Different colours and resins with different transparency in polymerized state are available. Some resins may be compatible with different printers, while others only with specific systems. Although the resins are delivered in darkened containers, it is best to store them in a dark and cool place. Elevated temperatures can also lead to partial polymerization, which will adversely affect printing quality.

- **Photopolymer resins offered by the company Stratasys**

Stratasys uses PolyJet's proprietary photopolymer 3D printing technology, practically analogous to material jetting printing. Although this technology differs significantly from laser stereolithography, photopolymer resins are used as the printing material. Because Stratasys photopolymer printers are designed for professional and industrial use, the company has developed its own range of printing materials. A feature of PolyJet technology is the ability to combine different photopolymers to obtain composite materials with unique characteristics (the so-called "digital" polymers).

- High temperature photopolymer

RGD525 withstands heating to a temperature of 75-80°C after heat treatment of the finished parts. The pure material is white.

- Transparent photopolymers

These are materials for imitation of transparent thermoplastics. They can be used in combination with rubber imitators to change the strength, as well as with coloured materials to obtain different translucent shades. They are designed to work with Objet Connex printers. RGD720 is a universal photopolymer for imitation of standard transparent thermoplastic materials. It has great strength and allow for creating details with smooth surfaces. VeroClear-RGD-810 is a strong, almost transparent material for polymethyl methacrylate imitation.

- Opaque strong photopolymers

This is a family of photopolymers for printing multi-coloured opaque parts with a high level of detailing. The standard set for the Objet30 Pro, Objet Eden and Objet Connex printers includes VeroWhitePlus RGD835 (white), VeroGray RGD850 (grey), VeroBlue RGD840 (blue) and VeroBlackPlusGRD 875 (black). The rich colour range allows for the creation of hundreds of different shades. Up to 46 colours can be used to build a part.

- Polypropylene imitation

Stratasys offers two materials that mimic polypropylene. Endur RGD450 is characterized by high wear resistance and the ability to create beautiful surfaces. It can be used safely in office conditions for the creation of both functional prototypes and finished products. Durus RGD430 is characterized by high impact resistance and breaking strength.

- Rubber imitation

The Tango photopolymer family is designed to imitate elastomers. This group includes: TangoGray FLX950 (grey), TangoBlack FLX973 (black), TangoPlus FLX930 (transparent) and TangoBlackPlus FLX980 (black).

- Biocompatible photopolymers

MED610 is intended for medical use. This material allows for the preparation of devices that require prolonged contact with the patient's skin (up to 30 days) or short-term contact with the mucosa (up to 24 hours). In addition, Stratasys offers two materials for use in the manufacture of hearing aids - FullCure630 (transparent) and FullCure655 (pink).

- Dental photopolymers

Stratasys offers three variants of resins used in dental prosthetics. VeroDent MED670 allows for the production of products in vertical resolution up to 16 micrometers and high detail. It is characterized by high strength and durability. VeroDentPlus MED690 allows for the application of layers with a thickness of 16 micrometers, and VeroGlaze MED620 is a white acrylic material used in the manufacture of crowns.

- Digital ABS plastic

Digital ABS plastic is produced by mixing RGD515 and RGD535 during printing. The finished material has high heat resistance and strength, comparable to real ABS plastic.

- **Photopolymer resins offered by the company Digital Wax Systems**

The company Digital Wax Systems manufactures stereolithographic printers and materials for jewellery, dentistry and industrial design. Digital Wax Systems offers three series of materials (DC series, DM/DL series and IRIX series) designed to create high-precision master models used for the production of jewellery and dental molds. The materials from the IRIX series imitate natural stone and are available in the following colours: white, black, red, green and ivory. IRIX photopolymers are designed for prototyping and production of finished products.

- **Photopolymer resins offered by the company 3D Systems**

3D Systems offers a wide range of photopolymer resins for use with ProJet 1000 and ProJet 1500 printers. *VisiJet FTI* is a series of materials designed for ProJet 1000 and ProJet 1500 printers using multi-ink printing technology. The different materials in the series differ in both colour and physical characteristics. Materials of this type have high strength and are suitable for creating high-precision functional prototypes. They are available in the following colours: ivory, red, grey, blue and black. *VisiJet FTI Zoom* allows for increasing the printing speed by 40% while maintaining the quality of external surfaces.

- **Photopolymer resins offered by the company 3D Ink**

The company 3D Ink offers two variants of photopolymer materials - *UV Resin* and *UV Resin Clear*. *UV Resin* is a universal material that hardens when exposed to white, blue and ultraviolet light. It can be used with relatively low-power light sources. The resin is convenient for use in the preparation of master models (mock-ups) of foundry molds. It is non-toxic, slightly irritating to the skin and mucous membranes and does not generate vapours. Overheating can cause premature polymerization. Uncured material can be reused.

Figure 2.3. Photopolymer resin UV Resin offered by the company 3D Ink

- **Photopolymer resins offered by the company RapidShape**

The company RapidShape manufactures photopolymer resins designed for both modelling and molding and used in the manufacture of jewellery, hearing aids and dental prosthetics. The materials offered by RapidShape are: *GP 101* (orange), *CP 200* (red), *CP 200* (yellow), *MP 300* (light brown) and others.

- **Photopolymer resins offered by the company FunToDo**

Fun To Do resins are manufactured by the Dutch company with the same name. The company offers three main materials based on acrylic. It is also possible to order specialized materials. The standard photopolymer resin version is compatible with all types of stereolithographic 3D printers. It has a high polymerization rate and is suitable for printing layers of 20 to 50 micrometers. The industrial version has increased strength and resistance in a wide temperature range (from -45°C to 225°C). Both versions are available in red and black. The foundry version is designed for 3D printing of combustible master models used in the creation of foundry molds for metal products made from bronze, copper, silver, iron, etc.

Figure 2.4. Photopolymer resin offered by the company Fun To Do

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Fun To Do photopolymer resins have a faint odour and do not cause severe irritation when they get in contact with the skin. They have a high rate of hardening and a very low degree of shrinkage (they lose only about 0.5% of their volume during hardening).

Metals

Unlike polymers, which are used in various forms (solid filaments, powders, resins), 3D metal printing almost always uses powders. Metal printing makes it possible to create high-quality and functional details from various metal powders. The distribution of powder particles in size, shape and flowability (the forces acting on individual particles as they flow) are important properties that determine how suitable the metal powder is for 3D printing.

Any metal and powder alloy can be used as materials. Stainless steel, cobalt-chromium alloys, titanium, etc. are successfully used.

Other materials

Some 3D printing technologies use ceramics (usually a polymer filled with ceramic powder) or composites (carbon-filled filament or metal-nylon powder). Polymers filled with ceramic powder have high wear resistance, which makes them an ideal material for making tools. Carbon, aluminium, graphite, and glass are added to the SLS powder to improve its strength and durability. FFF uses many exotic filaments, such as PLA polymer filled with wood or metal powder, which leads to a unique appearance of the printed objects.

Wood-polymer composite materials

LAYWOO-D3 is designed for printing products that look like wood (Fig.2.5). It consists of 40% microscopic sawdust and 60% binder polymer. *LAYWOO-D3* is very easy to use, as no preheated build platform is required. It is non-toxic and completely safe. The unique properties of the material allow different visual results when printing with different nozzle temperatures. The operating temperature range is from 180°C to 250°C. As the extrusion temperature increases, the colour of the material becomes darker and allows different types of wood to be imitated. The finished parts are machinable.

Fig.2.5. Filament LAYWOO-D3

BambooFill has been developed as an alternative to *LAYWOO-D3* by the Dutch company ColorFabb. The composite is made of 80% polylactide and 20% bamboo fibres.

It should be noted that the cost of wood-polymer composites is higher than the cost of other more widely used printing materials such as polylactide and ABS.

Imitation of sand

Laybrick is a composite material, a combination of a polymer matrix and a mineral filler. *Laybrick* allows for the creation of products with different surface textures. At low extrusion temperatures

(165°C-190°C) the finished products have a smooth surface. Increasing the printing temperature makes the surface rougher (sandy). At extrusion temperatures above 210°C the surface acquires a high degree of similarity with natural sand. The material is easy to work with, as no preheating of the build platform is required, no deformations occur during hardening and no toxic fumes are released when the material is heated. The only disadvantage is the higher price.

Imitations of metals

BronzeFill is a transparent polylactide with a filler of bronze microparticles. The finished products are easy to polish and can thus achieve an external resemblance to metal products. At the same time, it should be considered that the connecting element of the material is a thermoplastic with its corresponding mechanical and temperature limitations.

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Main stages in 3D modelling and printing

3D printing technology is a process of transforming virtual digital models into physical objects. The 3D modelling and printing process consists of the steps shown in Figure 3.1.

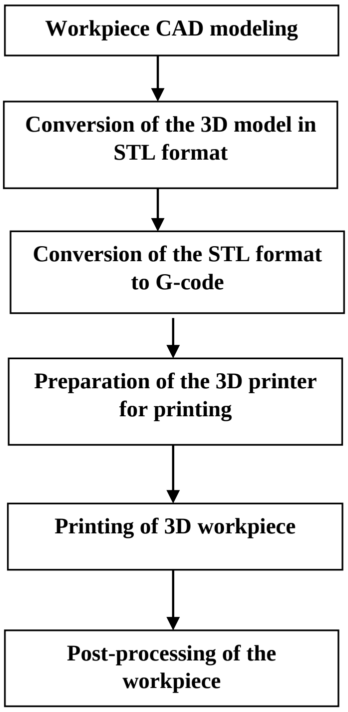


Figure 3.1. Main stages in 3D modelling and printing

CAD modelling of the workpiece

The process of 3D modelling and printing starts with the development of a virtual digital model of the future object. The models are created with the help of CAD software packages (computer-aided design). Depending on the degree of complexity of the part, it takes from several hours to several days to create its digital model. In some cases, 3D scanners can be used to create the virtual image of objects. In this case the accuracy of the objects decreases, and they become slightly blurred. To obtain a high-precision object, it is necessary to create it with a CAD program. Ready-made virtual models can also be found on the Internet on specialized sites for 3D printing.

Converting the 3D model to STL format

When the modelling is complete, the resulting file should be converted to STL (**ST**ereo**L**ithography) format, which is recognized by modern 3D printers. The format describes the surface of the object as a triangular mesh (a representation of a 3-dimensional surface in triangular facets). Most CAD programs have the ability to export the model as a STL file. This is done by selecting *"Save as type"* or *"Import/Export"* depending on the program used. Most programs require the user to set the level of detailing (accurate/rough). The quality of the 3D prototype depends on this parameter. If the parameter "accurate" is selected, the mesh will be dense, the finished file will take up significant space on the computer's hard drive and will be further processed by special software. As a result, the user will receive an object with a high-quality surface. If the parameter "rough" is selected, the mesh will be less dense; the finished file will take up less space on the hard disk and will be processed faster by the specialized program. As a result, the quality of the external surfaces of the object will be significantly lower than with accurate conversion. When choosing the method of conversion, it is necessary to consider the requirements for the quality of the external surfaces, and the capabilities of the personal computer to handle the processing of the model before sending it for printing.

Converting the STL format in G-code

The STL file with the future object is processed by a special program (slicer) that translates it into a control G-code for the 3D printer. If the model is not converted to G-code, the 3D printer will not recognize it. Slicer programs cut the model into thin horizontal plates and convert it into a digital G-code understandable to a 3D printer. The "slicer" program sets the trajectory of the print head when depositing the printing material and indicates the sequence of the material deposition during 3D printing. Once the G-code has been generated, the object is sent for printing.

Preparing the 3D printer for printing

The preparation of a 3D printer for printing depends on the printer type. For example, the preparation of a 3D printer with FDM technology requires that a special self-adhesive foil should be glued to the build platform and the polymer filament spool should be loaded. If bubbles form under the foil, they need to be removed by piercing with a needle. Before printing, it is recommended to remove any traces of grease on the foil by wiping it with alcohol. The next step is to load into the 3D printer a polymer filament spool of the desired colour. The spool should be placed on the stand and the end of the filament should be trimmed in order to be flat. The end of the filament is placed in the feed opening and moved forward into the extruder.

Printing of the 3D object

The 3D printing process depends on the technology. For 3D printers with FDM technology, the finished object is shaped on the build platform. During printing, the platform moves along the Z axis. The print head moves along the X and Y axes. It applies the molten polymer filament on the build platform layer by layer, shaping the finished object. The process of 3D printing is not complicated. The print head deposits the first layer of molten thermoplastic polymer in the work area, then the build platform moves downwards by the thickness of one layer and the printing of the next layer on the surface of the previous one starts. After the printing of all layers has been completed, the build platform moves downwards until the finished object appears. Depending on its complexity, it can take several hours for the printer to print the product.

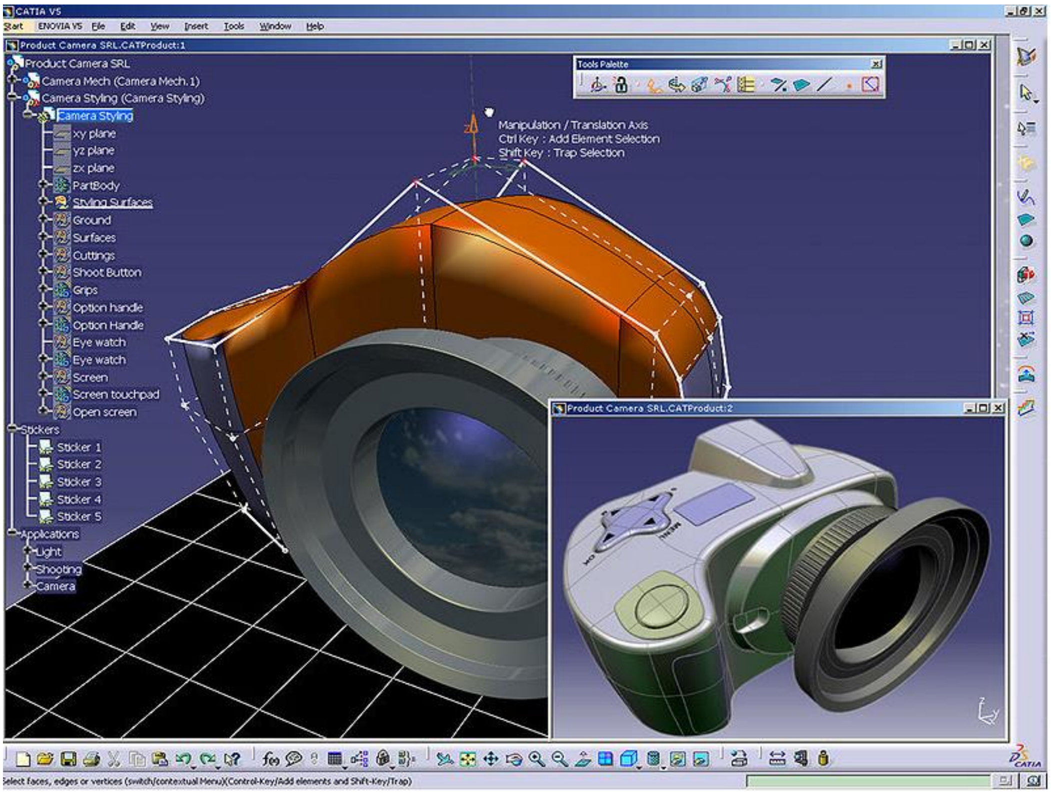
Post-processing of the object

The post processing procedures vary depending on the 3D printer technology. For some printing technologies, this is the separation of the printed part from the build platform. If the printed product includes elements from a supporting structure used during printing, they should be removed. If the supporting elements are printed from the same material as the product, their removal may be complicated because the surface of the object may be damaged. Therefore, in most cases, special additional materials are used for the supporting structure and they can be easily removed during post-processing without leaving traces on the product surface.

Software products for the creation of 3D models

CATIA

CATIA (abbreviation of "computer-aided three-dimensional interactive application") is probably the best 3D printing software for professional users. CATIA (https://www.3ds.com/products-services/catia) was initially developed in 1977 by the French aircraft manufacturer Avions Marcel Dassault. Initially the product was called CATI, but in 1981 it was renamed to CATIA when Dassault established its subsidiary "Dassault Systèmes" to develop and sell software. CATIA provides the unique opportunity to model complex products. This is a multi-platform software package for computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), product lifecycle management (PLM) and 3D.



Manipulation / Translation Axis
Ctrl Key : Add Element Selection
Shift Key : Trap Selection

Select faces, edges or vertices (switch/contextual Menu)(Control-Key/Add elements and Shift-Key/Trap)

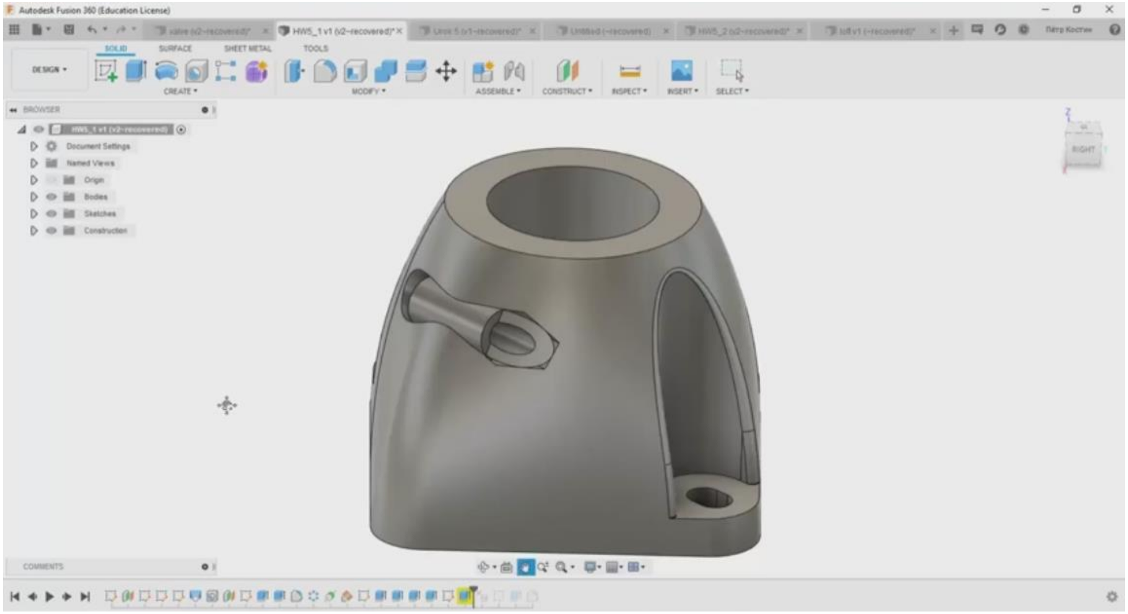
Because it supports many stages of product development – from conceptualization, design and engineering to production – it is considered as CAx software and is sometimes referred to as a 3D product lifecycle management software package. It facilitates collaborative engineering through an integrated cloud service and is suitable for use in a variety of disciplines, including surface and shape design; electrical, fluid and electronic systems design; mechanical engineering; systematic engineering; etc. The software loads a library with all the materials needed for the development of projects of varying complexity. Unlike other 3D modelling tools that require powerful computers, CATIA can run on inexpensive desktops and laptops. It is used in a wide range of industries, from aerospace and defence industries to packaging design.

Price: available on request

Platform: Windows/Unix

Fusion 360

Fusion 360 (https://www.autodesk.com/products/fusion-360/overview) is a cloud-based 3D CAD software developed by Autodesk. It handles the entire process of designing, testing and executing 3D structures. It provides full control over the design of shapes and offers reliable functions for creating highly detailed operating modes. This allows prototypes to be created and projects to be tested before their rapid production. In addition, stresses caused by static loads on the printed part can be determined and unnecessary areas in the project can be identified in order to reduce unnecessary loads. This can significantly reduce the cost of prototyping. Overall, due to its full range of modelling tools, Fusion 360 is one of the products preferred by designers and engineers.



Price: 30-days free trial version /USD 495 for one year/ USD 1,335 for 3 years.

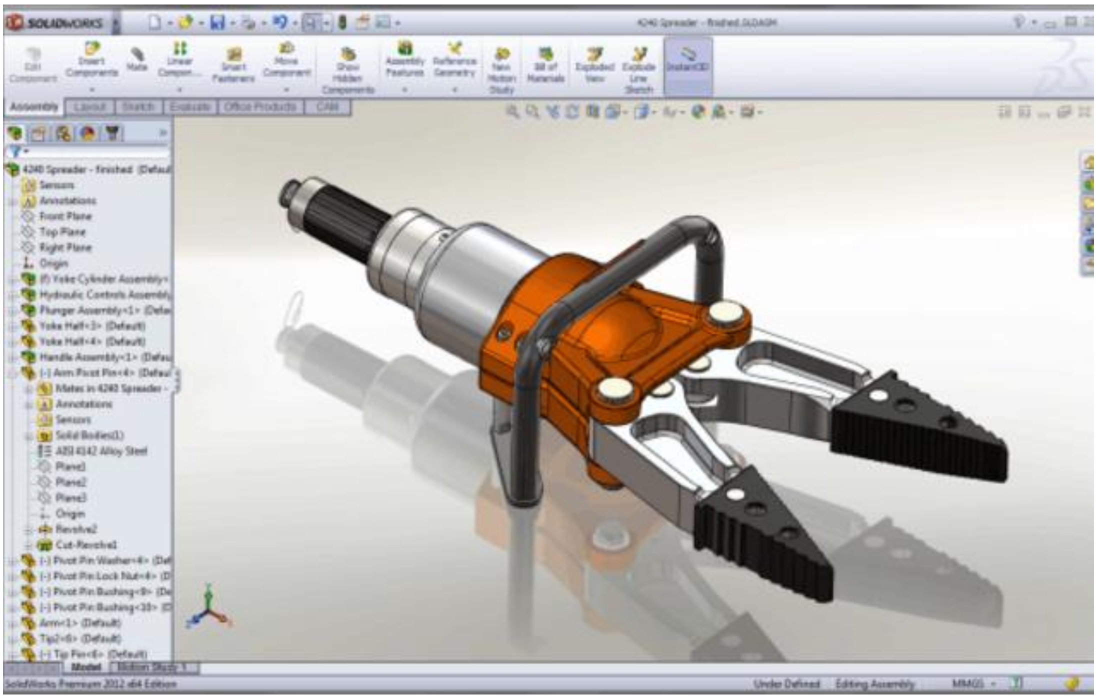
Platform: Windows/macOS

SolidWorks

SolidWorks (https://www.solidworks.com/domain/design-engineering) is a software offered by SolidWorks Corporation for computer-aided design (CAD) and computer-aided engineering (CAE) on Microsoft Windows. It offers a wide range of specialized design and modelling tools to easily create 2D and 3D models. Its main advantage is the ease of use and the user-friendly interface. This is the reason why it is the most commonly used mid-range CAD product.

SolidWorks Corporation was founded in December 1993 by Jon Hirschtick, a graduate of the Massachusetts Institute of Technology. He hired a team of engineers to create 3D CAD software that was easy to use, affordable, and operational on Windows. The company launched its first product, called SolidWorks 95, in November 1995. Since then, a total of 30 versions of the software have been released. The latest version is SolidWorks 2022.

SolidWorks is a 3D software for engineering design in the field of mechanical engineering, industrial equipment, consumer products, automotive industry, aerospace industry, robotics, energy, etc. It is a comprehensive environment offering a wide range of tools for design, research, visualization, data management and other functions. Each new version of SolidWorks provides improvements in sketching, assembly visualization, working with sheet materials, etc. SolidWorks offers additional functionalities for analyzing stress, strain, motion, tolerances and rendering; huge component libraries; routing for pipelines, pipes and cables; productivity tools; etc.

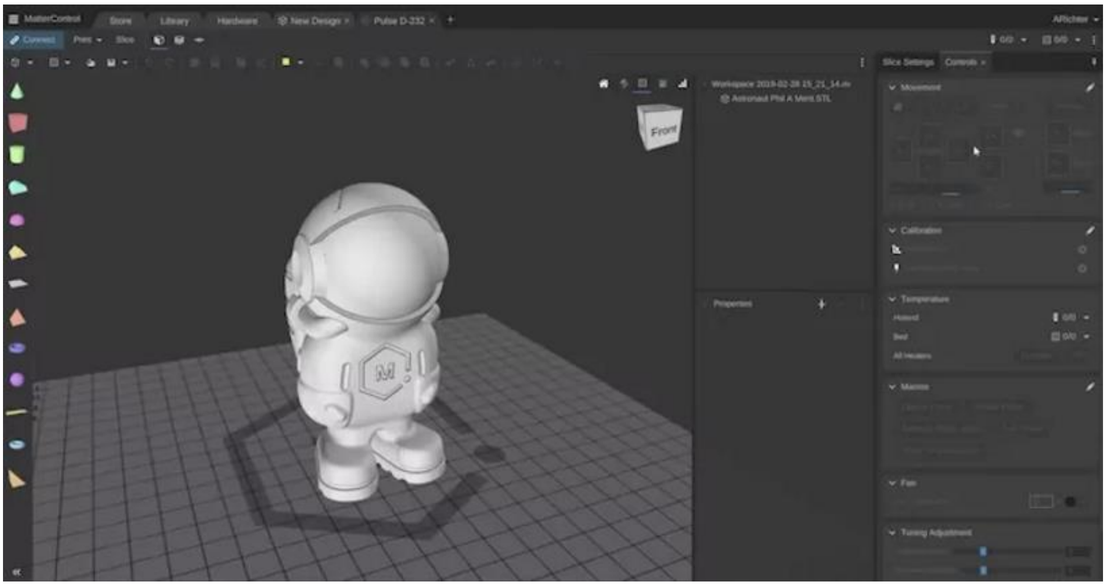


Price: available on request

Platform: Windows

MatterControl

MatterControl (https://www.matterhackers.com/store/l/mattercontrol/sk/MKZGTDW6) is a free open-source software used to design, cut and manage 3D prints. In addition to being a CAD modelling program, MatterControl is also a slicer and a host for the 3D printer. Thanks to the host features, it can control printing when the printer is connected to a computer via USB. With MatterControl, the objects can be designed using the design tools or visiting Design Apps to view existing projects. Projects can also be cut using various advanced settings for custom support generation, software bed alignment and integrated double extrusion controls using powerful 64-bit processing. When all variables are controlled, printed can be done directly in MatterControl, which eliminates the need for many programs. The software product has advanced 3D design features that facilitate the creation of high-quality models characterized by high complexity. It supports real-time Z-offset modification and has built-in dual extrusion controls using powerful 64-bit processing. If the user has a dual-extrusion printer, the software makes it easy to choose which extruder should print certain parts. Once the model is created, the user can remove and replace parts and give instructions to the printer which extruder to use for certain areas of the structure.



Price: free

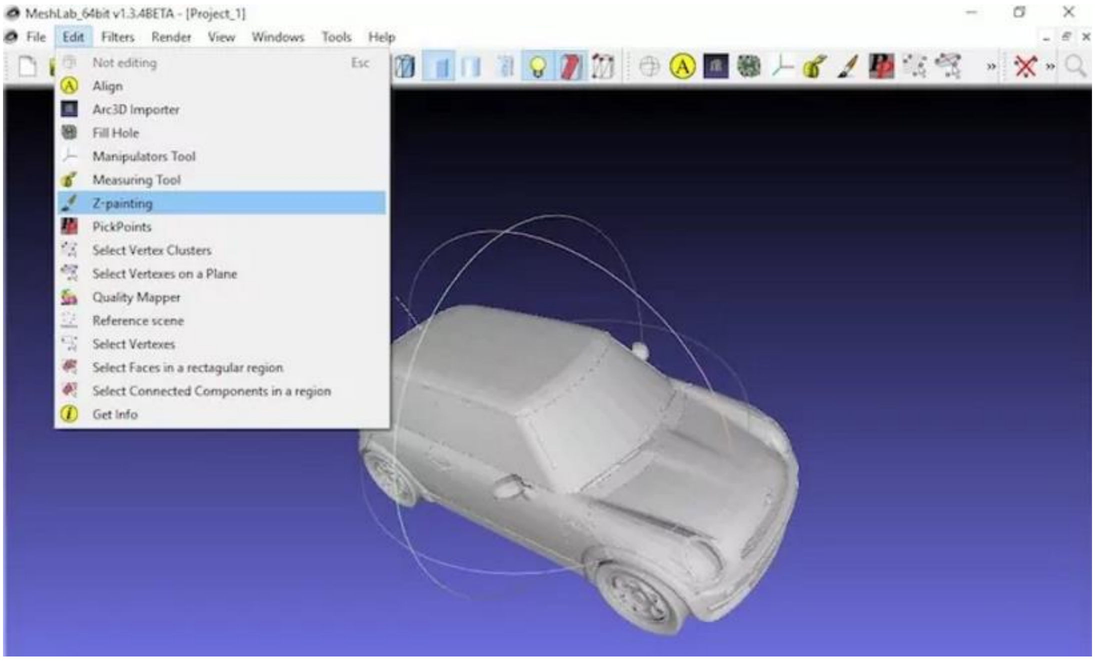
Platform: Windows/macOS/Linux

MeshLab

MeshLab (https://www.meshlab.net) is an open-source program for editing and processing three-dimensional triangular meshes. It contains many functions for checking, editing, texturing, rendering and converting meshes. It offers functions for processing raw data received from 3D digitizing devices and for preparing models for 3D printing. MeshLab is designed as a system tool for general 3D mesh processing. Users without high 3D modelling skills should be able to use it (at least its most basic functions). Advanced users should be able to change and expand it by adding functionality and or by changing all the parameters involved. The program is focused on mesh processing rather than on mesh editing and design.

MeshLab is a network viewer application where a three-dimensional object stored in various formats can be easily loaded and interactively scanned. It supports an ever-increasing variety of 3D formats (all common formats are supported). After loading a mesh, the user can work on it through a large set of direct parametric filters that perform automated tasks without supervision, such as smoothing, moving or simplifying. The user can also work through interactive tools.

With MeshLab's visualization feature, the smallest details of the 3D model can be graphically presented, the camera's perspective can be controlled, and built-in canonical views can be used. Different meshes can be moved into a common reference system, the shapes of each object can be reconstructed and its scale, position and orientation can be easily managed. There are many filters similar to Photoshop to adjust colour settings of vertices and panels, such as brightness, contrast, saturation, sharpness, and smoothing. There are also additional filters for calculating the Ambient Occlusion and Volumetric Obscurance and for mapping them to vertex or face colour. MeshLab is used for rapid prototyping in orthopaedic surgery, the production of desktop systems, as well as in many academic and research applications such as surface reconstruction, cultural heritage, and microbiology.



Price: free

Platform: Windows/macOS/Linux

Rhinoceros

Rhinoceros (https://www.rhino3d.com) is a universal 3D modelling software product based on NURBS (a mathematical model using B-splines commonly used in computer graphics to represent curves and surfaces) to enable users to manage points, curves, surfaces, networks, and solids as they wish. There are no restrictions on complexity, degree or size. The development and evolution of Rhinoceros started approximately 20 years ago with the objective to provide marine designers with tools to build computer models that could be used for the propulsion of digitally controlled production equipment used in shipyards. It has an extremely detailed interface, which can have several types of screens, perspective views, floating views, clipping planes, two-point perspective and 3D stereo viewing modes. Built-in enhancement tools ensure that the 3D models used in the process have the highest possible quality. When it comes to drawing and rendering, the software makes it easy to develop 2D and 3D drawings. Users can control the image, and change shadows and light quickly. 64-bit support and advanced graphics co-processor support enable Rhinoceros to work with large point clouds. The latest version is compatible with various CAD products. The product is easy to learn and use and is available at an affordable price without maintenance fees.

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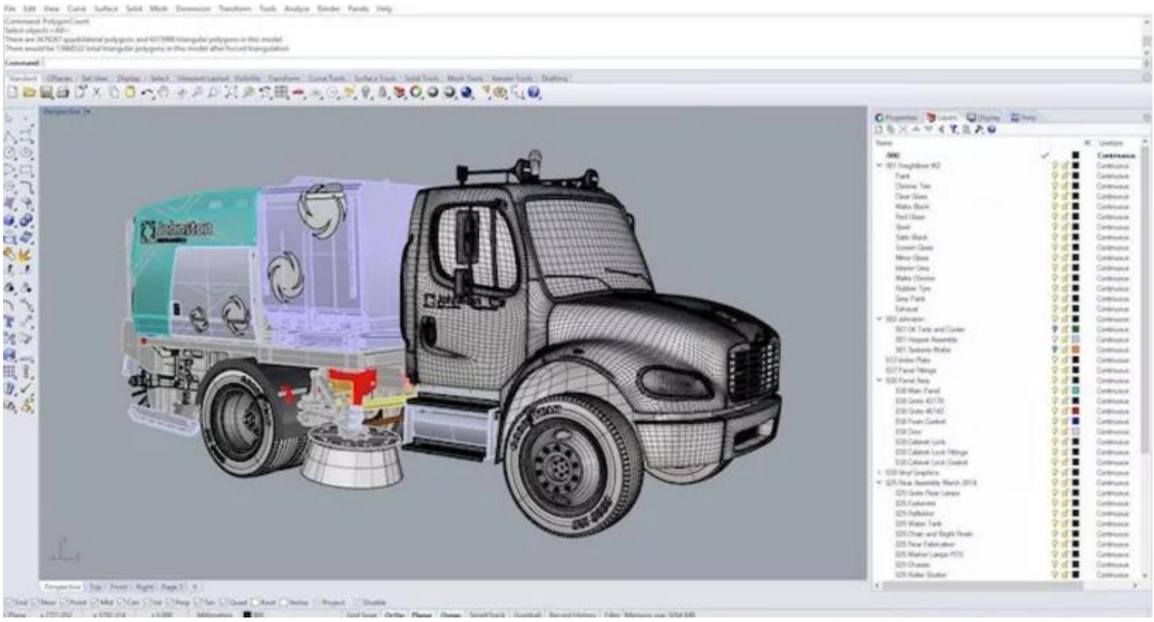


Price: free trial for 90 days/ USD 995 for permanent use

Platform: Windows/macOS

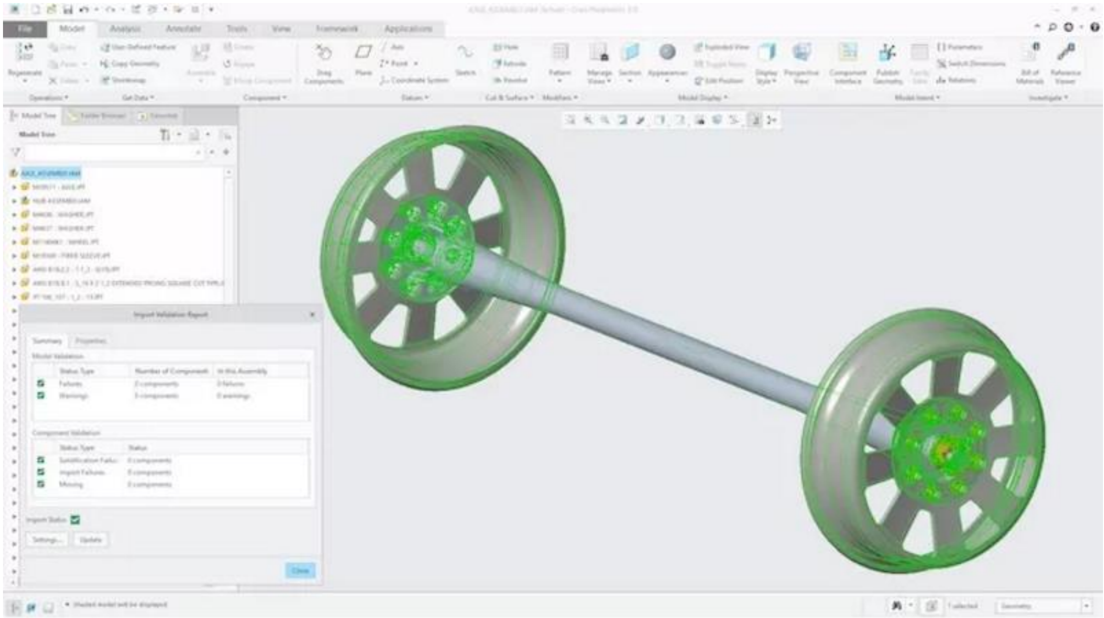
Creo

Creo (https://www.ptc.com/en/products/creo/packages) is a software package for high-quality design. It was developed in 2011 by Parametric Technology Corporation, a software development company based in Boston, Massachusetts. The product is easy to learn, and projects can move quickly from the earliest stages of product design to production. It combines powerful functionality with new technologies such as generative design, augmented reality, real-time simulation, additive manufacturing and IoT to reduce costs faster and improve product quality. Creo design packages provide comprehensive 3D software that can be expanded and upgraded to meet the changing engineering and business requirements.

Creo provides a package of computer-aided design (CAD) applications that support product design. The package consists of applications offering a different set of options to aid the process of product development. The parametric version of Creo deals with creation and editing of 3D models, while the model validation feature is a comprehensive and collaborative analysis tool for testing models. Creo Sketch is used to turn ideas into 2D sketches, and Creo Element is used to combine 2D and 3D parts into easy-to-learn software. Creo also offers an educational edition that is free and widely used in many institutions.

Creo works on Microsoft Windows and provides applications for 3D CAD parametric modelling of solid elements, 3D direct modelling, 2D orthographic views, analysis and simulation with the finite element method, schematic design, technical illustrations, and visualization. Creo can also be combined with Mastercam to quickly manufacture designed models. It significantly increases the speed of rapid prototyping in the industry.

The system requirements for Creo are relatively low. It is available for Windows 8 and Windows 10. The video display requirements are met by any 3D graphics card with openGL support. Creo Parametric requires 4 gigabytes of RAM and a minimum of 2 gigabytes of hard disk space. Internet access is required in order to refresh and connect to Creo servers.



Price: free trial for 30 days/ USD 2,480 for one year

Platform: Windows

OnShape

OnShape (https://www.onshape.com) is a universal product development platform that brings together all stakeholders in a single and secure cloud workspace. It makes extensive use of cloud computing, while processing and generating the model's digital image is performed on Internet servers. It is specifically designed for professionals who need version control and good collaboration capabilities. Team members can manage projects without storing copies of different versions of the files. The most impressive feature of this tool is its ability to help executives make the best business decisions using real-time analysis. This tool has proven its effectiveness in many industries, including 3D printing, mechanical equipment, machine parts, medical devices, consumer electronics, industrial equipment. Although the standard version costs USD 1,500, it is free for teachers and students. For amateurs, it can also be used for free for non-commercial, public and open-source projects.

OnShape is the only product development platform that can be deployed instantly on any computer or mobile device, allowing teams to work together quickly and at a global scale. Teams can experiment together or independently from one another to design alternatives without affecting each other's work. Real-time design previews, commenting, and simultaneous editing allow for a collaborative workflow in which multiple design iterations can be completed in parallel, and when approved, the best elements can be combined into the final design. Product specifications and drawings can be immediately shared with the production team or with suppliers.

In file-based CAD, product design and intellectual property are subject to unauthorized duplication, data corruption or even accidental sharing. The solution based on the OnShape database eliminates such security risks. There are no files to copy or manage. Designs are stored and tracked with a complete version history, allowing changes to be audited or cancelled. Strict role-based access control keeps design data always protected. Each designer, engineer, contractor, or supplier involved in the product design lifecycle receives specific permissions and rights. When the contract is terminated or the engineer leaves the company, access to the project may be terminated immediately.

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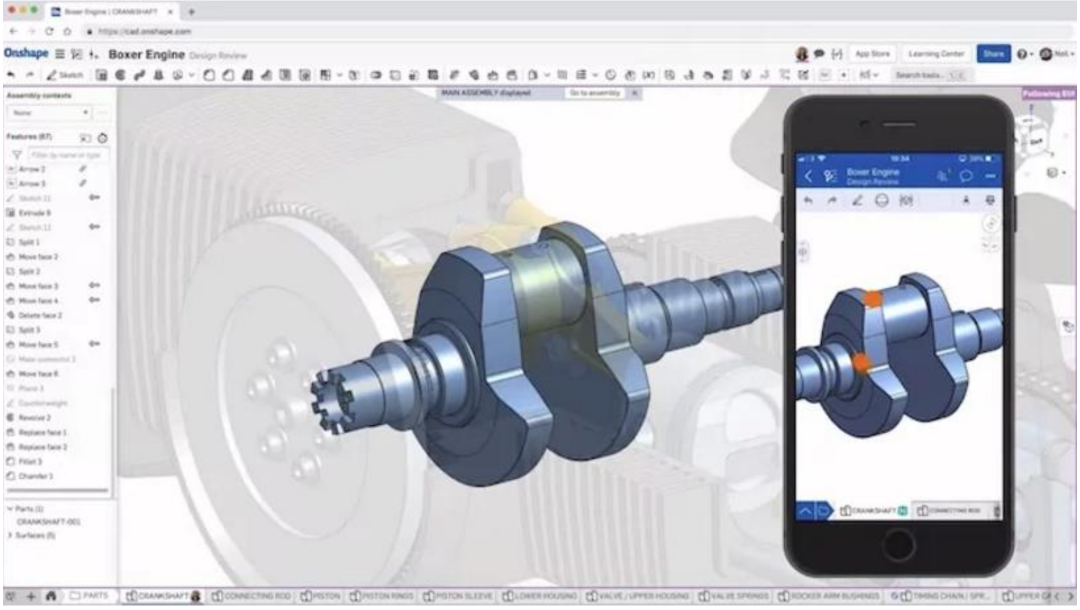
OnShape is the only product development platform that includes real-time data management. When a team member anywhere in the world makes a change in the design, everyone else can immediately see it. Built-in version control significantly reduces costly manufacturing errors. Distributed teams can simultaneously explore alternative design ideas and choose the best solution. The simplified CAD preview mode allows the sales team to show customers the latest product designs, share models with vendors to get earlier offers, or send early prototypes to the marketing department. Up-to-date analysis and reporting tools offer project stakeholders greater transparency and facilitate project management.



Price: USD 1,500 per year

Platform: Web browser/iOS/Android

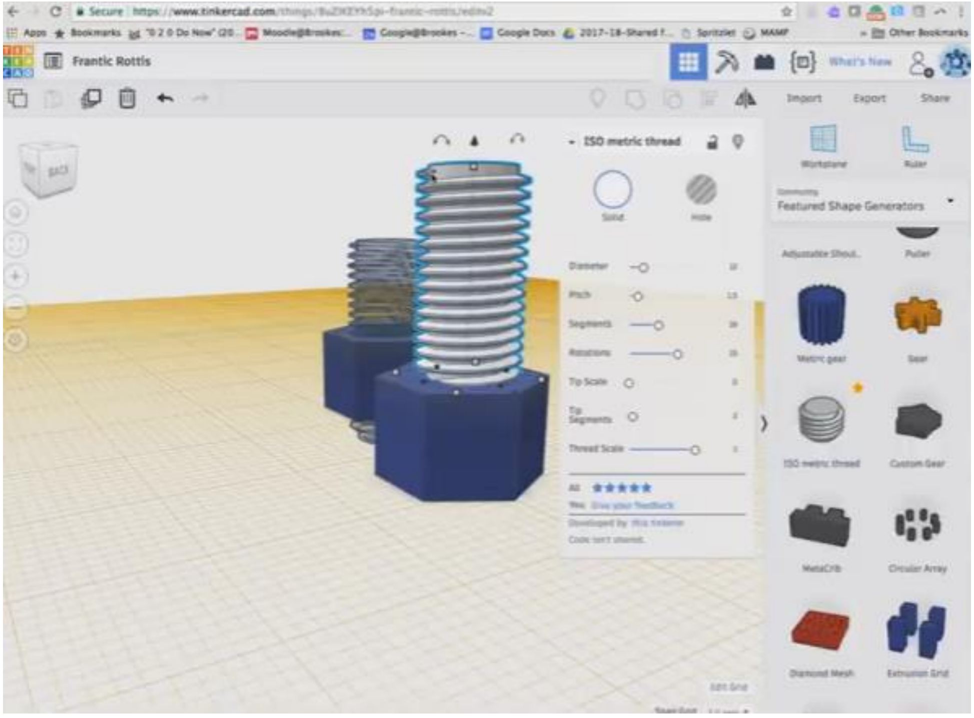
Tinkercad

Tinkercad (https://www.tinkercad.com) is a free, online 3D modelling program running in a web browser. Since becoming available in 2011, it has become a popular platform for creating 3D printing models. It has also been used for entry-level introduction to constructive solid geometry in schools.

Tinkercad was founded by former Google engineer Kai Backman and was co-founded by Mikko Mononen. The objective was to make 3D modelling, and especially the design of physical objects, accessible to a wide range of users. In 2011, the site tinkercad.com was launched as a web-based 3D modelling tool for WebGL-enabled browsers. In 2013 Tinkercad was acquired by Autodesk.

Tinkercad uses a simplified constructive solid geometry method of constructing models. A design is made up of primitive shapes that can be either “solids” or “holes”. By combining solids and holes together, the user can create new shapes, which in turn can be designated as solids or holes. In addition to the standard library of primitive shapes, a user can create custom shape generators using a built-in JavaScript editor. Shapes can be imported in STL and OBJ formats for 3D, and as 2-dimensional SVG shapes for extruding into 3D shapes. Models can be exported in STL or OBJ formats, ready for 3D printing.

Tinkercad has several advantages. It is free and has an intuitive interface that is very easy to learn. It is optimized for 3D printing. In addition, there is no need to run it on a powerful computer. However, it requires stable Internet connection.



Price: free

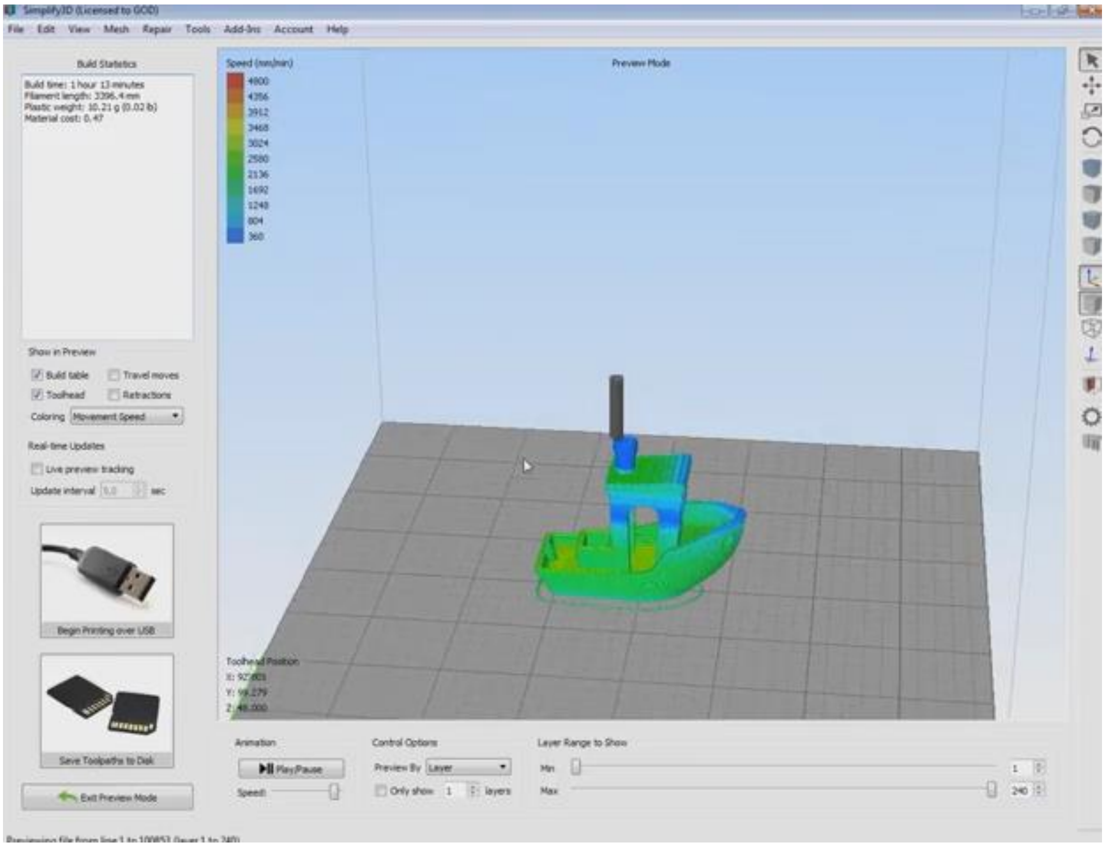
Platform: Web browser

3D slicer software (Conversion to G-code)

A slicer is a program that divides a 3D model into layers and prepares it for printing on a 3D printer. Thus, the slicer converts a 3D model (STL file) into a G-code file with specific instructions for the 3D printer how to print each layer. The program is called a slicer because it cuts the 3D model into multiple flat two-dimensional layers from which the 3D printer assembles the physical object.

Simplify3D

Simplify3D (https://www.simplify3d.com) is compatible with practically all 3D printers, regardless of the number of extruders and other design features. The software can quickly edit the 3D model. The user can change the settings and set the parameters for the extruders, manage the layers, change the fill methods, the temperature, change the G-code. In one print job, different parts of the model may have different settings, such as layer thickness. Simplify3D allows for importing 3D models in order to have them modified and optimized. It includes tools for analysing and repairing the model, correcting errors in STL files and preparing for printing. It processes large and complex files in STL, OBJ and 3MF formats faster than other common slicers. Simplify3D implements automatic generation of supports, as well as their manual relocation and removal. The latest version - Simplify3D 4.1 - provides greater control over the printing process and new features applicable for the latest generation of 3D printers. It supports up to 6 extruders, which allows up to 6 materials or colours to be used simultaneously. Its testing on many 3D printers shows a significant improvement in accuracy.



Build time: 1 hour 13 minutes
Filament length: 3396.4 mm
Plastic weight: 10.21 g (0.02 lb)
Material cost: 0.47

Toolhead Position
X: 92.805
Y: 99.279
Z: 48.000

Layer Range to Show: Min 1, Max 240

Previewing file from line 1 to 100853 (layer 1 to 240)

Price: free trial for 2 weeks/USD 149 for permanent use

Platform: Windows/macOS

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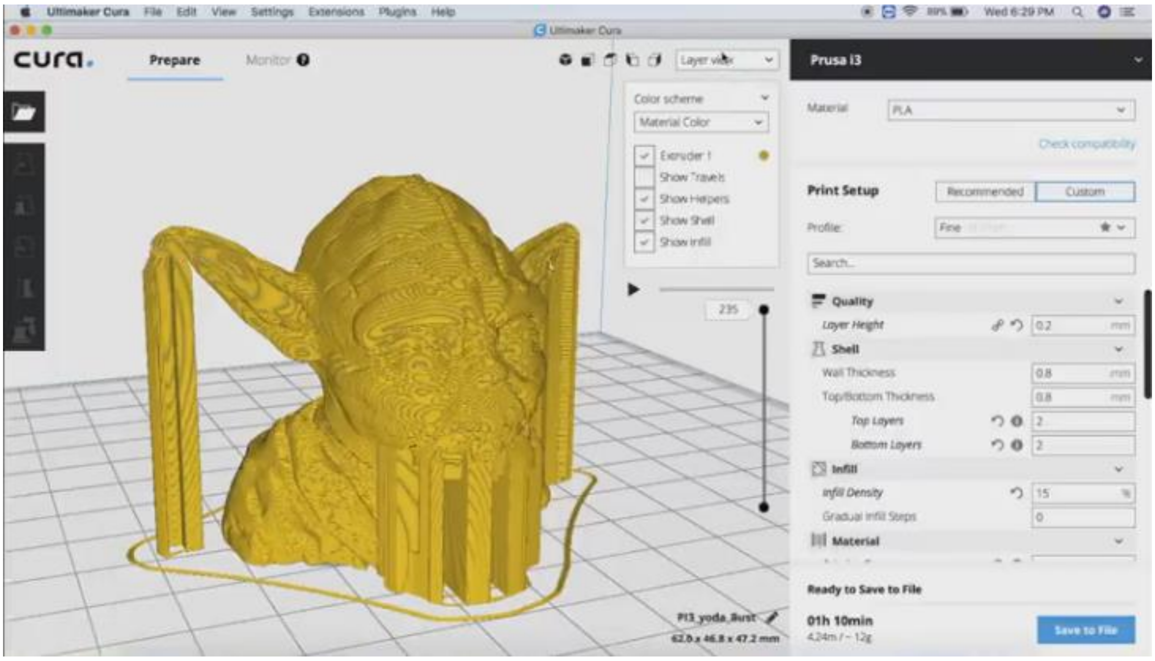
Cura

The Slicer Cura (https://ultimaker.com/software/ultimaker-cura) is an open-source software developed for Ultimaker's 3D printers. It is compatible with various other brands of 3D printers and can work with files in STL, OBJ, X3D, 3MF, BMP, GIF, JPG and PNG formats. The program shows the trajectory of the print head, the printing time and the consumption of material. It is distributed for free and is suitable for both beginners and advanced users. Beginners can quickly adjust the basic parameters, while advanced users can take advantage of more than 400 settings. Cura has a nice graphical interface and is easy to use. It allows the use of two materials for printing. Large STL files are processed quickly. Regular updates constantly improve features and printing.

Cura can directly control the 3D printer. To do this, it should be connected to the computer during the whole process of printing.



Material: PLA

Print Setup: Custom

Profile: Fine

Layer Height: 0.2 mm

Wall Thickness: 0.8 mm

Top/Bottom Thickness: 0.8 mm

Top Layers: 2

Bottom Layers: 2

Infill Density: 15 %

Gradual Infill Steps: 0

Ready to Save to File

01h 10min

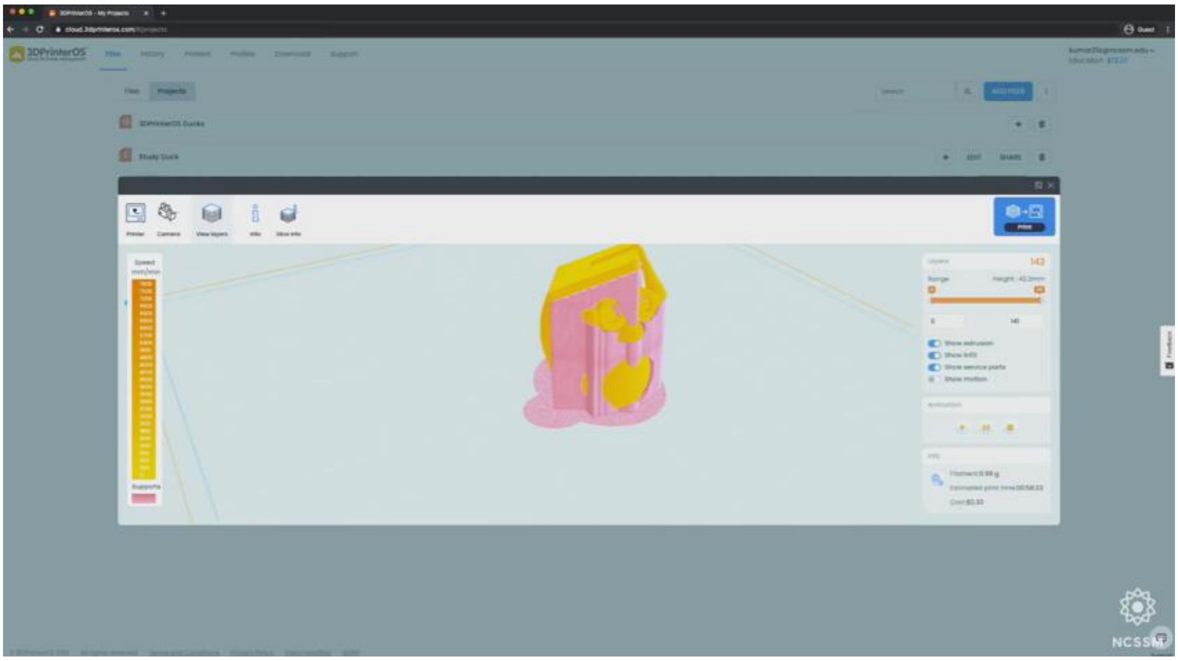
4.24m / ~ 12g

Price: Free

Platform: Windows/macOS/Linux

3DPrinterOS

3DPrinterOS (https://www.3dprinteros.com) is a cloud service with many settings for 3D printing. To use the program, the user must connect the 3D printer to a computer and run the program through a browser or desktop application. 3DPrinterOS can be used to edit models, and load and print objects from 3D hubs, including industrial equipment. 3DPrinterOS works with all printer models and has the highest levels of security for encrypted 3D printing processes in the industry. If the required printer is missing from the list, the developers promise to add it on request. The program includes three slicers: standard ("Cloud Slicer", "Slicer 2") and a special "Makerbot Slicer". Cloud Slicer and Makerbot Slicer are virtually identical in functionality. During work, the user can indicate his/her level of proficiency – "Beginner", "Advanced" or "Expert". There is also a functionality allowing for calculating the approximate cost of printing. When working in "Slicer 2" presets can be generated based on the input data, or manual settings can be specified. The program can also track the printing process in real time and is suitable for both professionals and beginners.



Price: free basic version/premium version – USD 200 per year

Platform: Browser /Windows/macOS

Astroprint

Astroprint (https://www.astroprint.com) is a cloud platform designed for custom 3D printing by 3DaGoGo Inc., a San Diego-based technology company. Astroprint is a software that allows the user to control desktop 3D printers from any web device without any prior technical expertise. 3D printing is performed with the help of the Astrobox device, which is connected to the printer via USB. Print control and printer management can be performed from any device that is connected to the Internet. The program is compatible with most printers, but if the required device is missing from the list, the developers promise to add it on request. Astroprint can load 3D models from integrated web services, such as Yeggi or from the CGTrader and Thingiverse repositories. It is possible to adjust the print sequence. Astroprint operates by taking a user-loaded STL file, adding a support bed, slicing the file, and saving the G-code to the user's online account. The user then can access, download, modify and print the model wirelessly through their 3D printer. If an error occurs during printing, the user can always connect to 3DprintCloud and correct the model. The Astroprint interface is very simple. In the Beginner user mode, it is necessary to select only the required quality and the print material. Many other settings are available for professionals.

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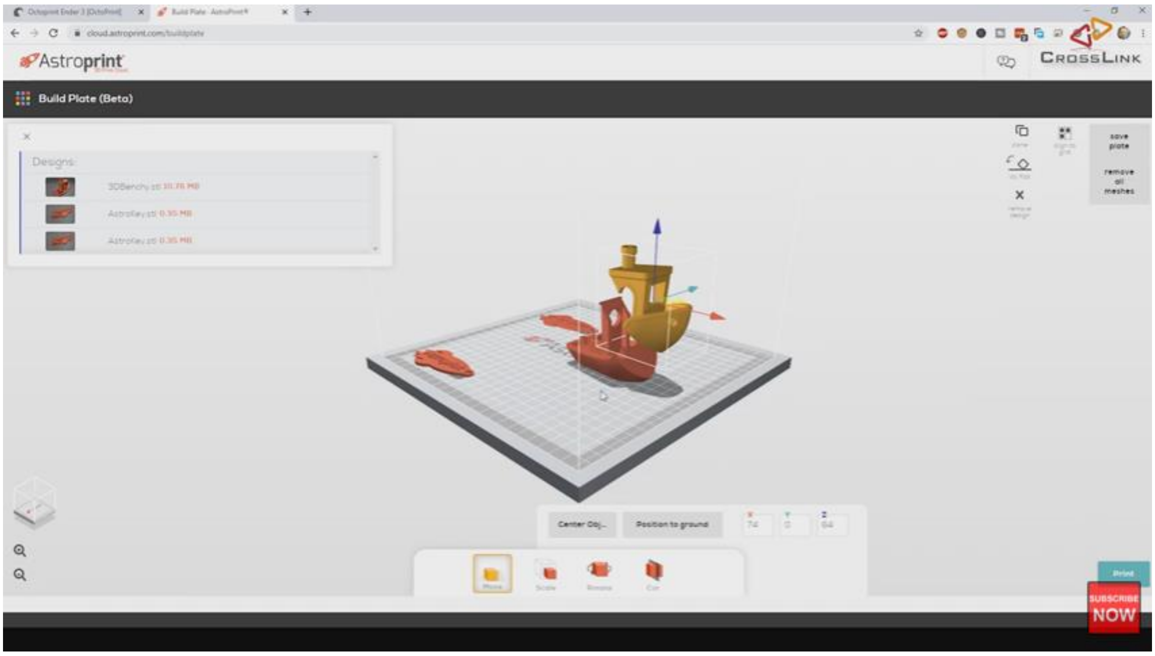

Price: free

Platform: Browser

Slic3r

Slic3r (https://slic3r.org) is a free open-source software that generates G-code from STL, OBJ, AMF and 3MF files. It is independent of any trading company or printer manufacturer. It can process complex models and estimate the time needed for parsing the G-code. The program supports all known variants of G-code (Marlin, Repetier, Mach3, LinuxCNC, Machinekit, Smoothie, Makerware, Sailfish). Slic3r has many configuration parameters that allow the users to configure and fully control their projects. For example it can control the printing speed to ensure enough time for the layer to cool before depositing the next one. There is a function for previewing the model in real time so that the user gets a better idea of what the printed 3D object will look like. To increase the printed part's strength, it is possible to specify that the next layer should not repeat the print pattern of the previous one.

Slic3r was developed in 2011 in the RepRap community as an attempt to provide the evolving 3D printing technology with open and flexible tools. The code and algorithms are not based on other previous work. As a genuinely non-profit project, Slic3r allowed users to experiment with several novel features that have become common since then, such as multiple extruders, micro layering, bridging perimeter detection, command line slicing, variable layer height, "honeycomb" infill, mesh slicer, dividing objects into parts, avoiding crossing perimeters, different extrusion widths, etc. All these features were introduced for the first time in Slic3r.

In addition, Slic3r integrates OctoPrint and can print to multiple devices simultaneously. Slic3r is the first slicer program in which functions for support of several extruders were implemented. The software runs fast even on slow computers. If changes are made, only those sections that concern them are processed. A real-time slicing feature, 3D previews, 2D and 3D print head preview, 3D preview, extrusion calculation, and many other features are supported. Slic3r is designed primarily for advanced users.

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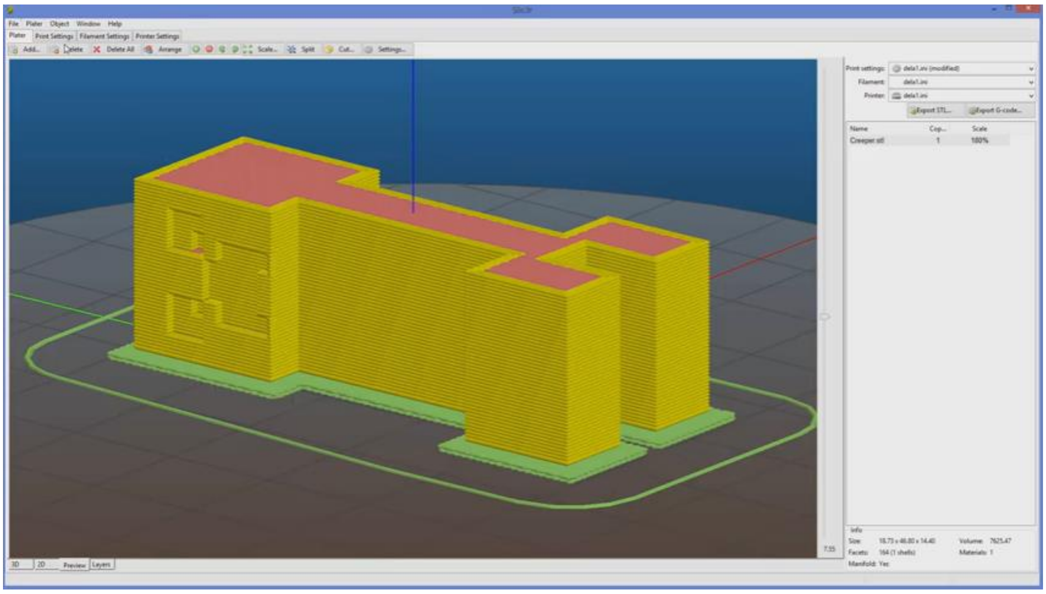


Print settings: dela1.ini (modified)
Filament: dela1.ini
Printer: dela1.ini

Name	Cop...	Scale
Creeper.stl	1	100%

Info
Size: 18.73 x 46.80 x 14.40
Volume: 7625.47
Facets: 164 (1 shells)
Materials: 1
Manifold: Yes

Price: free

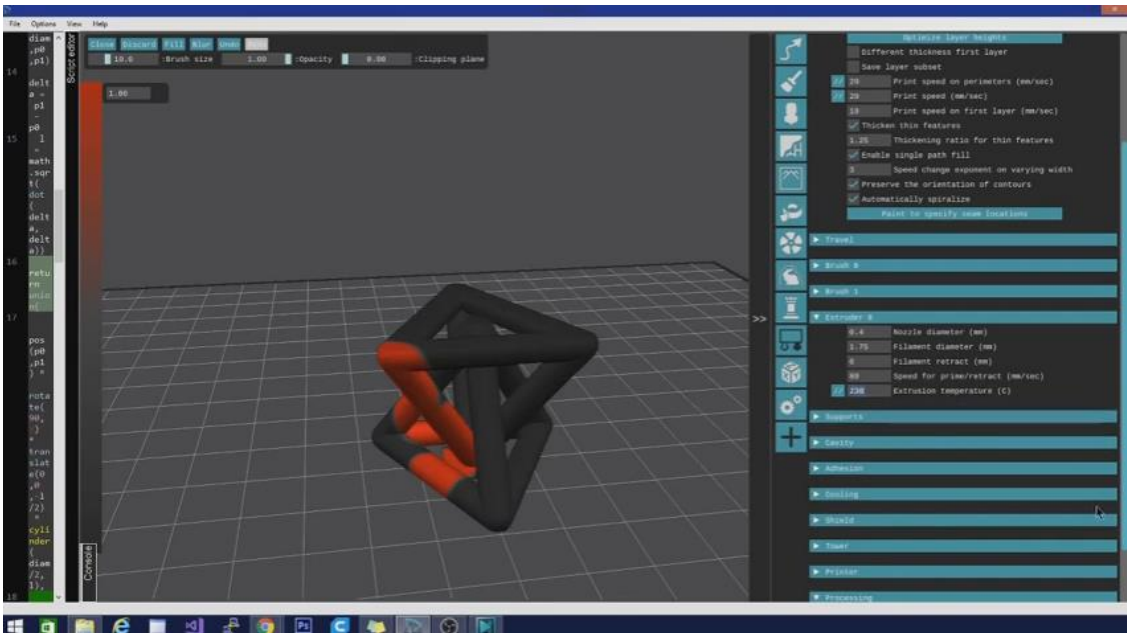
Platform: Windows/macOS/Linux

IceSL

IceSL (https://icesl.loria.fr) is not just a slicer, but a program with full functionality for 3D modelling. Its goal is to provide a powerful and affordable software for 3D modelling and slicing. It integrates several innovative ideas such as cubic/tetrahedral infills, bridge support structures, optimal adaptive layer thickness, progressive infills, efficient offsetting, tight protective shields, maximal self-supporting cavities, etc.

The core technology of IceSL consists of three different software applications:

- *IceSL-forge* is the most complete and powerful software. It combines modelling and slicing and provides great flexibility for modelling and making complex shapes. The modelling is done using scripts in a Lua-based language, which allows for describing Boolean combinations of shapes (triangular meshes, voxels, implicit surfaces, shaders). Thanks to modern imaging technology, all operations are performed interactively with real-time feedback and allow interactive customization of the model parameters. The technology allows efficient slicing and generation of instructions for the printer (G-code) without the need to go through the complicated process of creating a mesh.
- *IceSL-slicer* focuses on slicing. If given a 3D model (such as STL) or a geometry script (i.e. lua), it generate instructions for the 3D printer (G-code).
- *SliceCrafter* is an online version of the slicing feature. It is less powerful than IceSL-slicer but works entirely in a web browser.



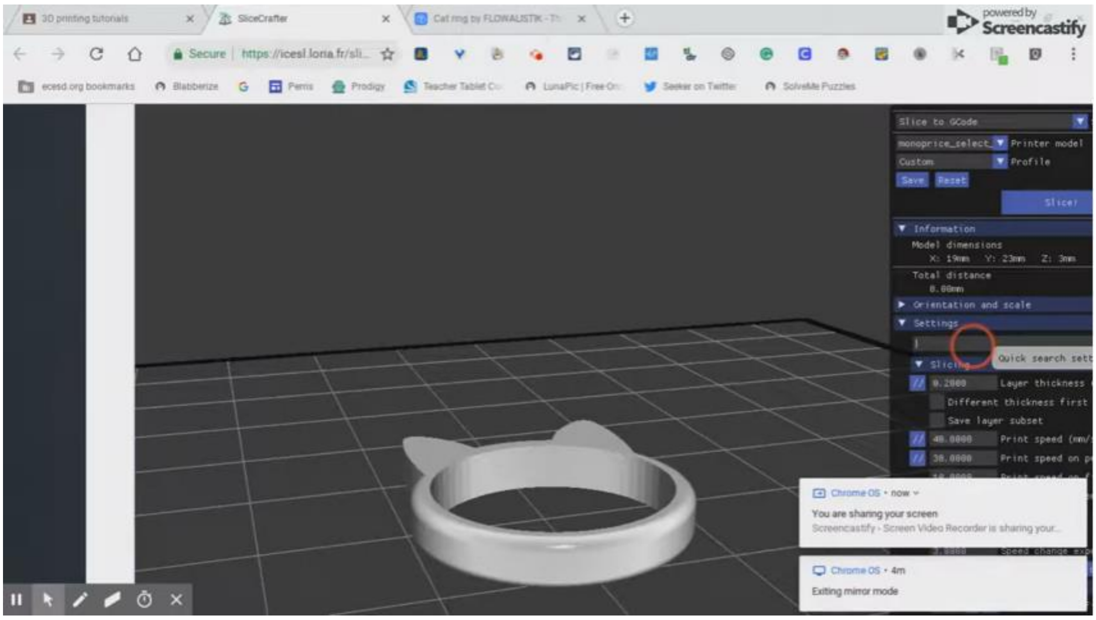
Different thickness first layer
Save layer subset
20 Print speed on perimeters (mm/sec)
20 Print speed (mm/sec)
10 Print speed on first layer (mm/sec)
Thicken thin features
1.25 Thickening ratio for thin features
Enable single path fill
3 Speed change exponent on varying width
Preserve the orientation of contours
Automatically spiralize
0.4 Nozzle diameter (mm)
1.75 Filament diameter (mm)
6 Filament retract (mm)
Speed for prime/retract (mm/sec)
Extrusion temperature (C)

Price: free

Platform: Windows/Linux

SliceCrafter

SliceCrafter (https://icesl.loria.fr/slicecrafter) is an online program based on IceSL. Compared to other 3D slicers, SliceCrafter is functionally somewhat limited, which simplifies the work of those users who do not want to delve into settings. The specificity of the software is that the G-code can be generated without installing the slicer on the computer and even without registration.



monoprice_select_ Printer model
Custom Profile
Model dimensions
X: 19mm Y: 23mm Z: 3mm
Total distance
0.00mm
0.2000 Layer thickness
Different thickness first
Save layer subset
40.0000 Print speed (mm/
30.0000 Print speed on p

Chrome OS • now
You are sharing your screen
Screencastify - Screen Video Recorder is sharing your...

Chrome OS • 4m
Exiting mirror mode

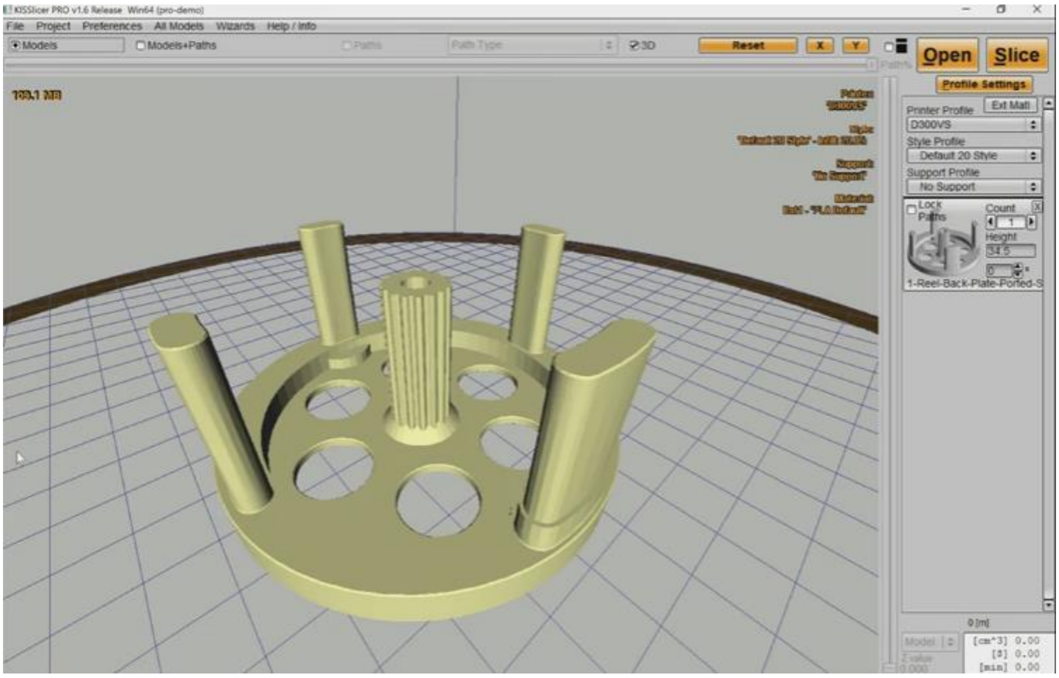
Price: free

Platform: Browser

KISSlicer

KISSlicer (https://www.kisslicer.com) is a powerful, easy-to-use and fast cross-platform application that slices STL files into ready-to-print G-code files. The free version of the software

(FREE) is suitable for users working with single-extruder printers. The paid version (PRO) allows for working with printers with many extruders. Although KISSlicer settings are rather complex, the slicer allows complete control over all printing processes. In addition, there are no special requirements for computer performance.



Price: Free/$ 35 per workplace (minimum 5 workplaces)

Platform: Windows/macOS/Linux

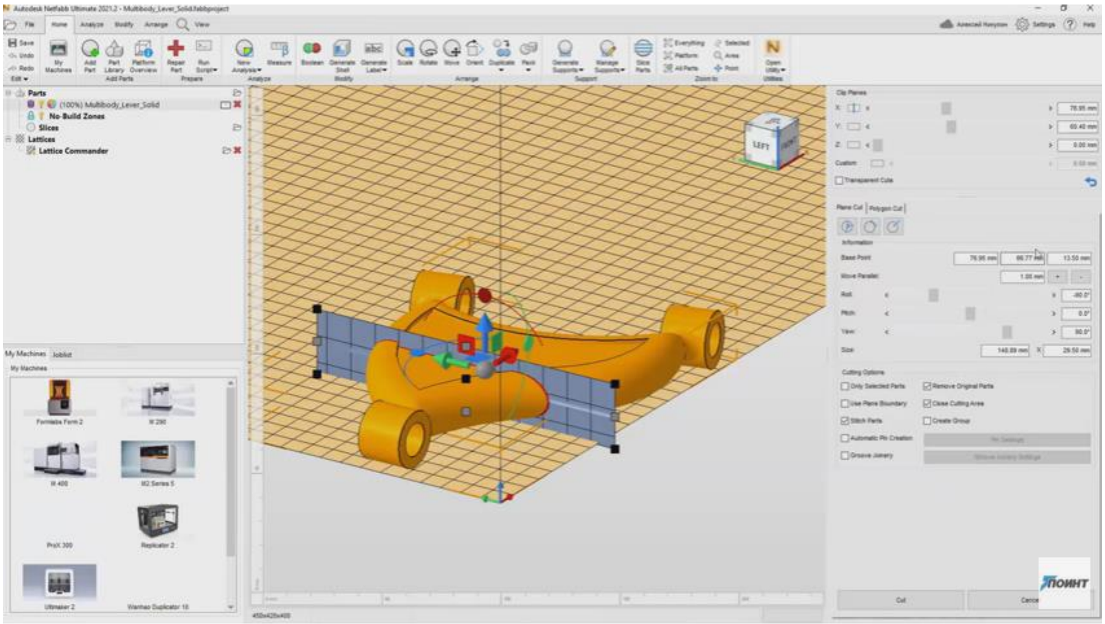
NetFabb

NetFabb (https://www.autodesk.com/products/netfabb/overview) is a slicer that includes additional capabilities for analysing, recovering and editing STL files. The development of NetFabb started as a free program that gradually became a powerful set of tools for STL file processing. In 2015, NetFabb was acquired by Autodesk, which divided it into several levels:

- NetFabb Standard is a basic version that allows quick preparation of the model for printing
- NetFabb Premium has advanced capabilities for creating grids, supports and automatic packaging of parts
- NetFabb Ultimate provides modelling tools, customizable Toolpath strategies, and also helps to automate the process of preparing the model for 3D printing
- NetFabb Simulation helps to model certain metal printing technologies before the start of production. This version is designed for the process of metal powder melting through targeted energy exposure. It allows users to run tests to ensure that their parts will be printed correctly.

Fusion 360 with Netfabb is one of the powerful additive manufacturing tools, applicable to the whole process from 3D model design to printing and post-processing with CNC machines. Autodesk programming support is designed for industrial production. The main advantages of NetFabb are: a professional program for working with 3D objects; huge selection of tools; integration in the CAD complex of Autodesk. The disadvantage is the high cost of the software license. A trial version for a period of 30 days is available, with which all professional functions can be tested. The annual license is USD 240 for the Standard version, USD 4,415 for the

Premium version and USD 13,790 for the Ultimate version. NetFabb can be used by advanced users and professionals.



Price: free trial version for 30 days/from USD 240 up to 13,790 (annual license)

Platform: Windows

Repetier

Repetier (https://www.repetier.com) is a high-performance software for 3D printing control and preparation of files for printing. This slicer is designed primarily to enable remote control of printers but it can also slice models. It can control printers with multiple extruders (up to 16 extruders) and is compatible with any 3D printer available on the market. The software has features for remote access via Repetier Server that allow the user to control the printer via a browser on his computer, tablet or smartphone. Another advantage of this slicer is the ability to set up the printer. It is necessary to note the user-friendly interface and temperature settings. This is especially useful when adjusting PID controllers or checking axial movement. Limited slicing settings are a disadvantage. Another disadvantage is that the software is inappropriate for users without at least a medium level of training.

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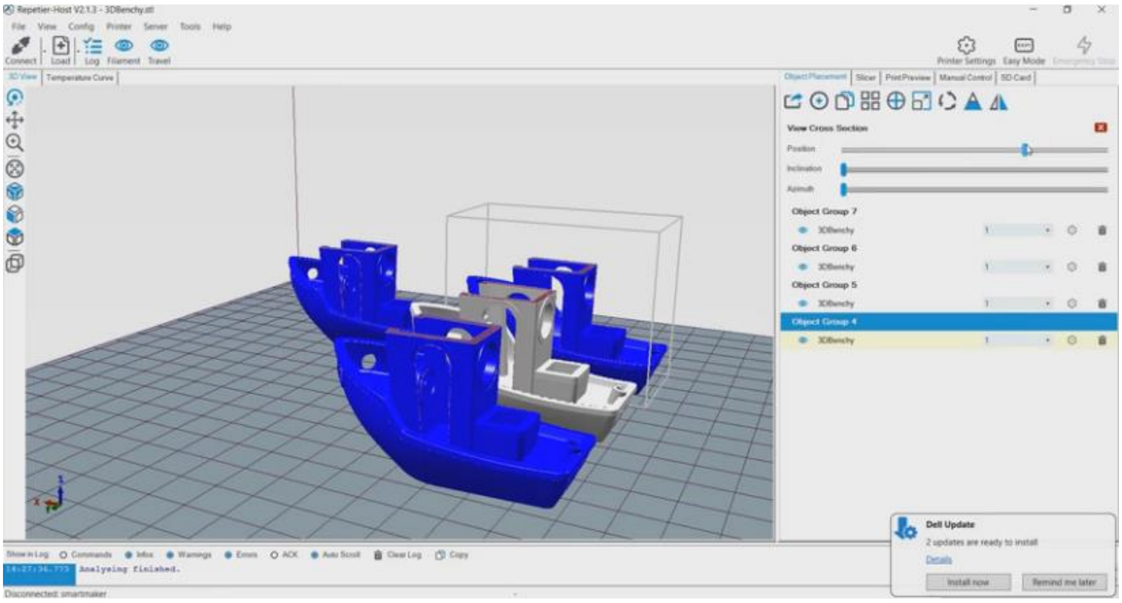


```
14:27:36.773 Analyzing finished.
```

2 updates are ready to install

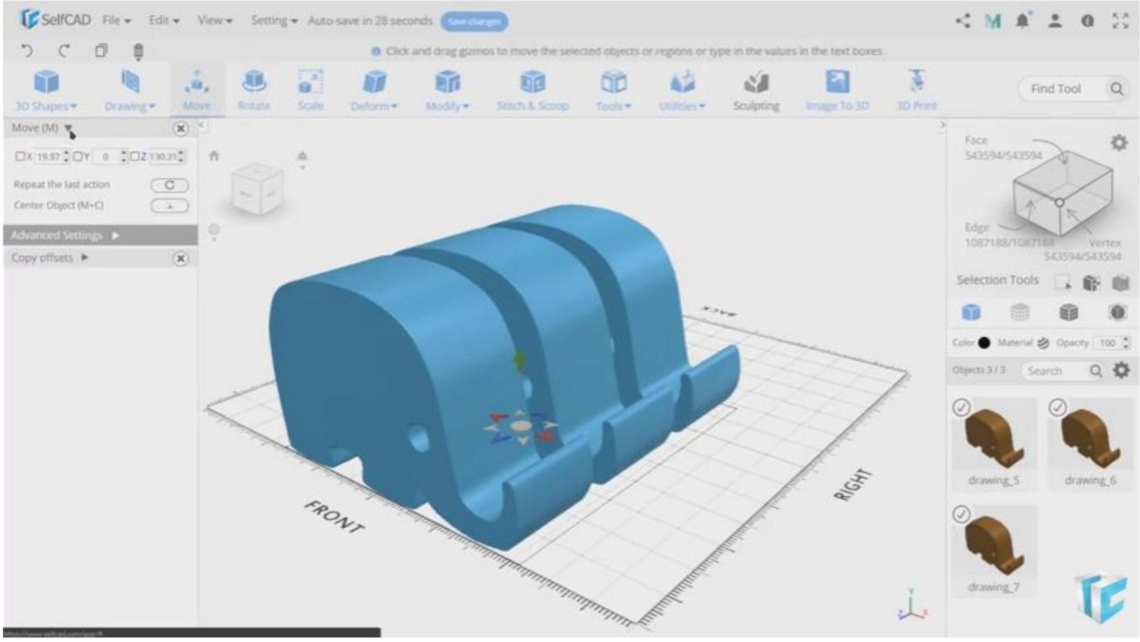
Price: free

Platform: Windows/macOS/Linux

SelfCAD

SelfCAD (https://www.selfcad.com) is an online software for 3D modelling, slicing and 3D printing, developed in 2016. It runs in the browser and the cloud and is based on polygonal meshes. Because it is browser-based, no downloads are required. The work can be saved in the cloud, but there is also an offline mode. The interface is significantly simplified, so novice users can easily work with the product. The software has many tools for creating and modifying objects, as well as built-in automatic generators of shapes, screws, nuts, spirals and images. It provides a database of completed 3D printing projects, as well as an extensive library of objects and parts. It is able to import models in STL and OBJ formats from other 3D design programs. Functions for changing the height of the layer, the type and density of the infill in percentages and the printing speed are implemented. It is possible to preview the layers, calculate the approximate printing time and the final weight of the model. Learning to use the software is not difficult and takes five hours. The program is operational on Windows 7, 8 and 10, Mac and Linux, and supported on Chrome, Firefox and Safari browsers.

Although SelfCAD is suitable for the mass consumer of all ages, it is specifically designed for students and classroom use. Switching from SelfCAD to higher-level engineering programs is easier for users with SelfCAD experience. The company emphasizes the use of SelfCAD within the educational sector. The so-called *SelfCAD for Schools* version offers additional features and support for schools and teachers. Some of these features include: access to a dedicated online storage database, additional safety and security measures, and additional support for teachers. A paid subscription is required to export projects to STL. The main advantages of SelfCAD are that it offers a large selection of tools, is suitable for users with different proficiency levels, and provides interactive training materials.



Price: 30 days free trial version/ USD 9.99 per month

Platform: Browser/Windows/macOS/Linux

Areas of application of 3D printing

Foundry production

3D printing enables the creation of master models (mock-ups) for foundry molds. The time needed to create a mock-up using a 3D printer is much shorter than the time to produce it in the traditional way. 3D equipment also allows designers to develop products with a geometry that is impossible to produce in the traditional way. It takes several hours to produce a high-precision mock-up using a 3D printer. The product will fully comply with the digital model.

3D printing enables the creation of foundry master models from two materials:

- *Wax*. This material can be used to create blanks for creating molds with a melting point of about 60°C, smooth surfaces and very good detail. 3D wax mock-ups are widely used in dentistry and jewellery production.
- *Photopolymer*: This material can be used to create combustible master models. The combustion temperature is about 600°C.

The creation of foundry molds using a 3D printer guarantees fast prototyping of the part, the ability to print a foundry mold of any complexity and low cost.

Architecture and design

Architecture and design are areas where 3D printers are used very actively. In recent years, 3D printing has become indispensable not only for large companies but also for small architectural offices. The reason for this is that 3D printing is causing a real revolution in the field of construction modelling and the creation of new creative objects.

The preparation of architectural mock-ups is an important task of any design office or architect. The quality of the mock-up is linked to the interest the future project can arouse in applicants, clients and potential investors. Modelling by traditional methods is a long, laborious and very expensive process. 3D printing technology allows to significantly reduce the time for mock-up development, to improve its quality and to ensure that it is as close to the original as possible. The main part of the design work is performed on a computer using modern software for 3D modelling.

The advantages of 3D printing of architectural models are:

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- *Short preparation time:* a few hours of operation of the 3D printer replaces 2-3 months of manual labour
- *Low price:* a special composite material based on gypsum is used
- *Finished models do not require painting:* 3D printing delivers the needed colours and shades
- *High quality of 3D printing*
- *Clear visualization of the model.*

3D printers from the ProJet x60 series (Zprinter), manufactured by 3D Systems, can be used to create full-colour architectural mock-ups. They build models from a special composite powder based on gypsum. The main advantages of these 3D printers are their high productivity and quality and the low cost of materials.

In addition, photopolymer 3D printers are often used to make large and complex models. They can build complex and highly detailed parts of the project with very small elements. These 3D printers cannot print coloured objects and the materials for them are significantly more expensive.

Some architects and designers use 3D printers operating with ABS thermoplastic. This reduces the cost because thermoplastics are cheaper than composite gypsum powder and photopolymers. In this case, full-colour and highly detailed designs cannot be created.

Mechanical engineering

Additive manufacturing is rapidly displacing existing technologies in all areas, including mechanical engineering. 3D printing allows solving a wide range of tasks quickly, efficiently, and accurately. It is used for:

- development of new workpieces and mechanisms (creation of conceptual models and test samples)
- modernization of existing systems and individual elements
- repair and replacement of defective parts.

The use of 3D printing at the stage of development or in the technological process allows creating products of higher quality cheaper and faster.

The advantages of using 3D printing in mechanical engineering are:

- *Ability to create details with unique geometry* that cannot be created in traditional ways.
- *Reduction of production time*: the 3D printer allows printing the finished product in a few hours, while traditional technologies take weeks and sometimes months
- *Elimination of the "human factor",* reduction of risks and errors. Products created with a 3D printer replicate the CAD model
- *Improvement of the parameters of finished products* – weight reduction, increased accuracy and strength
- *Ability to control the physical and mechanical properties* of parts by mixing different materials (e.g. alloys of different metals).

Modern 3D printing systems enable the quick and efficient solution of a wide range of tasks facing engineers and designers in mechanical engineering. 3D printers are indispensable at the stage of creating conceptual designs, as well as at the stage of production of finished products. They are applicable more specifically in the following cases:

- *Prototypes for testing:* Prototyping of future products before the start of serial production for the purpose of testing, verification of characteristics and functionality, and elimination of defects
- *Device housings and device components:* Unique housings, fasteners and other devices for devices and mechanisms that ensure their reliable operation
- *Production equipment:* quick development of convenient equipment for new production
- *Ready-to-use products:* printing of parts and details that can be used immediately – mechanical parts, repair parts, elements of engines and structures, tools.

Electronic industry

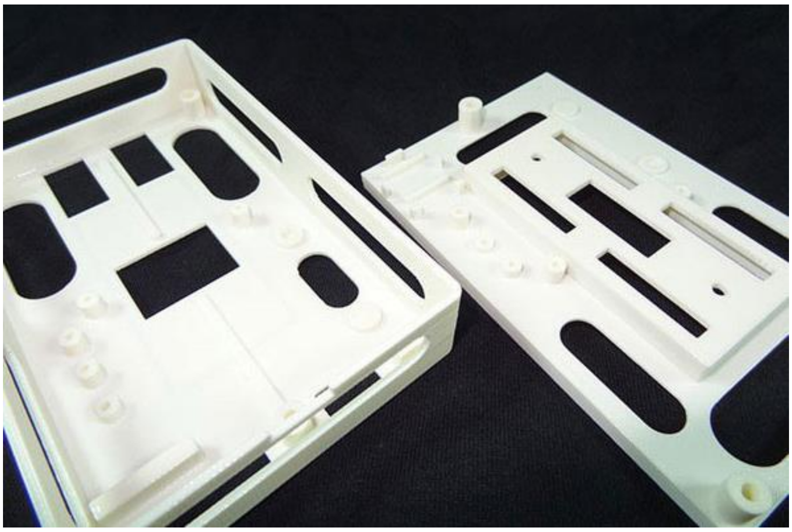
Manufacturers of consumer electronics and utensils are actively using the capabilities of 3D printing to optimize the deadlines and reduce the costs of development. 3D printers printing with different types of thermoplastic materials are widely used in instrumentation. Printers printing with polymer resins are also used to produce high-precision prototypes and models for testing.

Manufacturers of electronic devices use 3D printers mainly to produce:

- conceptual models for appearance assessment or marketing research
- test prototypes to test the functionality and ergonomics of complex systems
- ready-to-use products or individual elements.

The use of 3D printers in the electronics industry is necessary in particular in the following cases:

- *Reduction of deadlines:* it takes several hours to prototype a new device using a 3D printer.
- *Reduction of the product's price:* the cost of developing a product on a 3D printer is significantly lower compared to its production with a diecast mold.
- *Preservation of trade secrets:* a 3D printer in the office allows for keeping all the details of new developments within the company. It is not necessary to provide information to external contractors to produce the required part.
- *Extensive opportunities for testing and refinement:* it is possible to build quickly and cheaply as many prototypes as need, as well as to test and refine them to achieve the desired result.



Education and research

The 3D printing has been one of the main educational trends in recent years. Universities understand that without the use of 3D printers, students cannot be given real-world training. 3D printing improves the learning process by developing students' figurative thinking and creating skills for automated design. It significantly increases the interest in the learning process as it allows students to feel like innovators. Students can create a model on the computer and hold it in their hands a few hours later. This leads to strong motivation for training.

For the educational institutions themselves, 3D printers allow not only to increase their prestige, but also to train professionals capable of performing real design tasks. What is more, this can be done without significant costs for the purchase and use of equipment.

It should be noted that 3D printers are suitable for all ages. For younger students, 3D printing is interesting for general development, familiarization with the technology and use in game mode. High school students and university students appreciate the benefits of 3D modelling and printing from a practical point of view. They can realize their own projects, print practical assignments, and develop their creative abilities and habits.

3D technologies are especially popular in technical universities. Students design objects, details, and models in the classroom, make prototypes using a 3D printer, and evaluate and test them. 3D printing is already included in the curricula of many universities and enables students to realize their design ideas. With the help of 3D printers future architects and designers can realize their projects, and experiment with materials and shapes.

Jewellery

The advent of 3D printers is causing a real revolution in the jewellery sector. Before 3D, it took a lot of time to develop jewellery based on wax models. Now 3D printing allows for designing jewellery with specialized software, and for making a wax or photopolymer master model.

Jewellery 3D printers are characterized by high accuracy and speed of printing and very high quality of the created surfaces. The resulting products are very smooth and do not require additional processing or adjustment. Making jewellery with these devices is possible even for small jewellery workshops. At the same time, the cost of such work has significantly decreased.

Using this technology, the designer initially creates the model of the future ornament with a CAD program. The master model of the product is then printed using a 3D printer. The material can be a special wax or combustible photopolymer. After melting or burning the master model, a ready-to-use foundry mold is obtained. This process is significantly less strenuous and less expensive than the use of manual labour. In addition, 3D printing allows for eliminating mistakes in the production process that are due to the "human factor".

Consumer goods

Modern 3D printers provide the opportunity to quickly produce a wide range of popular consumer goods such as phone cases, souvenirs, statuettes and more. About 35% of such goods are produced using 3D printing. The 3D printer allows for the creation of unique products. The high printing speed allows for creating a ready-to-sell souvenir for a low price in just a few hours.

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It is possible to print full-colour items, and high accuracy ensures no errors. The simplicity of 3D printing makes souvenir manufacturing possible even in a small office.

Medicine and dentistry

Medicine was one of the first fields to appreciate the potential of 3D printers. Scientists from leading medical research centers have developed technologies and materials for printing dentures and implants and even a method for printing biological material. 3D printing ся used in the following medical fields:

- *Prosthetics:* this includes all metal and plastic prostheses which are in contact with tissues and are not included in the blood circulation cycle. Often such prostheses are developed in collaboration with the patients, considering all their needs and demands. The models consider the individual anatomical features of the person and can also be adjusted. A big advantage of these prostheses, apart from their functionality, is the price, which is many times lower than the price of traditional prostheses.
- *Implants:* these include internal organs in contact with the bloodstream and bone tissue embedded under the skin - elements of the skull, joints, vertebrae, etc. There have been numerous successful operations for transplanting heart valves, auditory ossicles, and blood vessel sections. Potentially working organs of the heart and lung type have been printed since 2011, but transplants of such prostheses have not been performed so far due to the high risk to life.
- *Bioprinting:* the technology is under development, but it is safe to say that it is successful and the implantation of the first internal organ printed from biological material is not far off.
- *Dentistry:* this is one of the first fields in medicine where 3D printing was used. Before the discovery of the possibilities of additive technologies, dental crowns used to take several weeks to make and their production was the task of dental technicians. Now the technology is sufficiently sophisticated to allow the dentist to print a crown on the spot based on a 3D photo of the patient’s tooth.

  3D printers have an increasingly important role in the work of any dental clinic or dental laboratory. With their help, dentists not only improve the quality of their services, but also reduce costs. In addition, 3D printers in dentistry guarantee very high accuracy of finished products. They save dentists from the complex and time-consuming process of manual modelling of dental prostheses, crowns, and other products.

  Customers no longer need to wait and go through a complex process from the first visit to the placement of the final structure, including a series of measurements and refinements. Now it is necessary to scan the oral cavity and the final result is achieved. Dental 3D printers make complex and outdated production methods unnecessary. Thanks to newer technologies and modern materials, a finished product is obtained several times faster. But the main thing is that the dental models printed on a 3D printer perfectly recreate all the nuances of the original sample. The main advantages of using 3D printing in dentistry are: possibility to storage all anatomical patient data in digital form; reduction of the time for development of the products, without any compromises in accuracy; a printing process that eliminates the human factor and increases the volume of production without the need for additional staff.

The advent of 3D printers has significantly changed the development of medicine. In the future we should expect even greater advances in the use of additive technologies.

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