3D4AUTO

Co-funded by the Erasmus+ Programme of the European Union

Handbook

ECVET based 3D printing curriculum and training module in automotive technology education

developed in the framework of the project titled

ECVET compatible 3D printing training modules for automotive technologies

acronym

3D4AUTO

action n.

2021-1-SK-KA220-VET-000034617

This publication was realized in the project "3D4AUTO" in the framework of the European programme Erasmus Plus KA220-VET. This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission and the NA cannot be held responsible for any use which may be made of the information contained therein.

TABLE OF CONTENTS

1 INTRODUCTION TO 3D PRINTING TECHNOLOGY IN AUTOMOTIVE EDUCATION

1.1 History of 3D printing

Stereolithography, commonly known as 3D printing, has existed since the 1980s. These first pioneers called it rapid prototyping technologies, so the term 3D printing was born. Although printing is only one part of the process, most prefer to use the term "3D printing" when we talk about technology in general.

In early 1980s, few people were able to realize the full potential of this amazing technology. For the first time, they used this early process as an affordable way to prototype products in certain industries.

Japanese lawyer Dr Hideo Kodama was the first person to file a patent for Rapid Prototyping technology. Unfortunately for him, the authorities rejected his request. Why? Because Kodama missed the one-year deadline, it was unable to file full patent claims in time. It was still in May 1980. Since Dr Kodama was a patent attorney, his trespassing was regrettable.

Four years after Dr Kodam`s French team of engineers decided to use the technology. Although they were very interested in stereo lithography, they soon had to abandon their mission. Despite their best intentions, there was no commercial interest in 3D printing. But this was not the end.

The mass expansion of 3D printing can be dated from 2009. It was caused only by the expiration of 3D print technology in automotive FDM patent protection (FFF) technology, improved computing power of computers and software and the development of new materials.

In 1986, Charles Hull successfully registered the first patent for stereo lithography (one of the 3D printing technologies where the photosensitive resin is cured by UV light). He was also the first person to invent a functional machine for this technology in 1992. This machine was able to print physical objects based on a digital master. This was probably the most important milestone for 3D printing. Charles later founded 3D Systems Corporation. A year later, the first 3D printer for SLS (laser sintering) technology was built.

In 1989, Scott Crump and his wife Lisa Crump invented the most widely used 3D FFF (FDM) printing technology today where plastic wire is melted and applied in layers. It is interesting how this idea came about. He tried to make a plastic frog for his daughter with melting gun with mixture of polyethylene and wax. After unsuccessful attempts, he decided to automate the production process so that thin layers were applied to each other. Crump later founded company Stratasys.

In 2004, Adrian Bowyer, a teacher of Mechanical Engineering at the University of Bath in England, founded the open-source project RepRap, whose idea was to print spare parts, which significantly accelerated the development of 3D printers. The Czech company Prusa Research was also created on this concept.

Figure 1-1 - xyzprint.eu

In 2009, patents for FDM (FFF) technology expired, which enabled a sharp drop in prices and thus a mass expansion of this technology for end users.

The transition to the 2nd millennium was exciting because the man was implanted with the first organ made by 3D printing. Researchers at the Wake Forest Institute for Regenerative Medicine extruded a synthetic version of the human bladder and the coated it with human cells. The newly formed tissue was then implanted in patients with little to no chance, that their immune system would reject them, because it was made from their own cells. From a medical point of view, it has been a great decade in the history of 3D printing.

In ten short years, scientists from various institutions and start-ups have created functional miniature kidneys, built a prosthetic leg with complex parts that were extruded in the same structure, or a bio print of the first blood vessels created using only human cells. It was also a decade when 3D printing moved into the category of open solutions. Adrian Bowyer launched the RepRap project in 2005 – an initiative based on open solutions to create a 3D printer that could essentially be built – or at least could print most of its own parts. In 2008, the self-replicating Darwin printer was introduced.

Suddenly, people everywhere had the opportunity to create their own things that they longed for. The Kickstarter project, which started in 2009 and has since received funding for number of 3D printing projects, has also been interesting. By the middle of 200, new approaches in production already reflected the requirements for customer solutions and also supported the idea of mass customization of products to customers. The first SLS plant became commercially viable in 2006, opening the door to industrial production on demand.

Start-up Object (now merged with Stratasys) focused on 3D printing created a machine that could print from multiple materials, allowing the production of a single product in different versions with different material properties.

The culmination of intensive creative innovations in this decade was the launch of the so-called collaborative collaboration, such as Shapeways, a 3D printing market where designers can get feedback from consumers and other designers and the manufacture their products.

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If we look back on the last few years and compare it with the present, we will not be far from the truth if we say that we are already living in the future. Well, almost. While the price of 3D printers has fallen rapidly and accuracy of 3D printing has improved, innovators are bringing improvements that Ch. Hull could only dream. Designers are no longer limited to printing with plastic. Today, you can print engagement ring of your dreams out of gold or silver. KOR Ecologic introduced the Urbee, a car with a body made using 3D printing, built so that it had a range of 85km/ liter on the highway.

In addition to jewellery and aircraft, 3D printing is now used to produce affordable housing for the developing world; visionaries began using technology to push everything from intelligent robotic arms, bone prostheses, and even various parts with a thickness of several atoms (resulting in even smaller electronics and batteries). Anyone who thinks that 3D printing is just about making small objects has to wake up, because engineers at the University of Southampton in England have built and successfully tested the first functional unmanned aircraft made by 3D printing.

The total cost was less than $7,000.

2013: Did you know that 3D printing technology became a hit after it was mentioned by the President of the United States in his speech? In his speech about state of the union address in 2013, Barack Obama praised 3D printing for having "potential to revolutionize everything we do."

The Swedish company Cellink launches the first standardized commercial printer for biodiesel. It is made from a material obtained from seaweed called Nano cellulose alginate, and the biodiesel can be used to print tissue cartilage.

Cellink`s first product cost $99 per refill. In the same year, the company also sold a printer priced at $ 4,999. The company`s latest addition is the BIO X printer, which is priced at $ 40,000. Thanks to these products, 3D bio printing is becoming a more affordable technology for a wide range of researchers around the world. Three random, great, unexpected facts about 3D printing: NASA is a major proponent of 3D printing – from food to the first weightless 3D printer in space. There is a 3D printer (Photonic Professional GT) on the market that can create objects that are no coarser that human hair. Louis DeRosa used a 3Doodler – a 3D pen to create a functional six- engine drone.

1.2 3D printing in automotive practice

The coming years will certainly bring further ground-breaking discoveries and milestones, which will lead to an even faster adaptation of 3D printing. Conventional production methods such as turning, milling, cutting, grinding, drilling and so on will not disappear so quickly. They may still be here for hundreds of years, although their utilization rates will decline more slowly rapidly.

In practice, 3D is used mainly for the production of plastic parts with dimensions up to 200x200x200mm (FFF/FDM technology). Due to lower accuracy and high production time, it is a piece or low-series production.

Nowadays, 3D printing has gained ground mainly in the following areas:

- School supplies
- Functional devices
- Functional metal parts
- Personalized products
- Design products

It is important to mention that, in general, additive production has the least technological and shape limitations compared to other production technologies. In practice, this simply means that what was not possible to produce 20 years ago is already possible with the advent of these technologies, which opens up completely new possibilities for using.

The main benefit of "free modelling" is the so-called topological optimization, through which we achieve an organic lightweight design.

Figure 1-2 - nextech.sk

One of the factors in the choice of production technology will be the economic aspect of production, but the flexibility of production is also gaining ground. In this, additive production is a clear winner. Compared to plastic injection into the mould, where we produce the first piece after about 8 to 12 weeks, the length of the production process is incomparably shorter. In the coming years, it will become increasingly important to produce quickly, with quality and to measure.

We consider mass personalization of products to be the main use of 3D printing. However, the total cost of production will be higher compared to large series. Therefore, the end customer pays extra. These costs are mainly the designer's time to prepare the model and set the machine parameters correctly. Subsequently, the time of production, the price of the material and possibly the final processing of the product.

1.3 Using of 3D printing in the educational process

Technical education deals with work with technologies and new areas of applied science in education. It emphasizes the understanding and practical application of the basic principles of science. Technical education aims prepare graduates of scientific or technical professions. In education, it is possible to print various teaching aids and resources through 3D printing to make teaching more efficient and help to the teaching itself. In secondary technical schools, 3D printing is helpful in various subjects, such as tools for logistics of products, road vehicles and their diagnostics in electrical engineering and electronics.

When it comes to the connection between 3D technology and education, in America MakerBot Academy, which is originated as an initiative for the development of education and knowledge development in science, technology and mathematics. The mentioned platform serves to create attractive educational content for school students and for teachers training to work with 3D printing. MakerBot Academy wants to provide a 3D printer to every school in America in the near future. It is mainly about preparing students for the future through teachers in the field of technology. MakerBot printers have moved 3D towards to the education system. The whole system of connecting 3D printing and schools is used to get to know and learn children work with new technologies. It is a gradual process of working with technologies from simple work on 3D projects through the using of various software in 3D printing to creating your own 3D projects.

The introduction of 3D technology into education and training has several aspects. One of them is undoubtedly the preparation of students to acquire and necessary skills for future careers and possible focus on further study.

In order to combine education and 3D technology, it is necessary to create a general curriculum, the aim of which will be to get acquainted with the process of working with children at high school. Students will learn about the control of various software programs and also with the process of working in 3D printing.

According to this curriculum, the preparation of students at secondary school is related to students aged of 14 to 18. The curriculum at the high school will focus on the skills needed to operate a 3D printer. For high school students, it is also possible to use more complex techniques in teaching, such as using a filler or working with a 3D printer with different temperatures. The plan will also focus on generating 3D content for printing.

Figure 1-3 - spsd.ba

Although a number of programs are being created to support schools so that they can work with 3D printing, the problems of introduction into education are mainly financial. Inadequacy with working with a 3D printer is also a problem. This creates limits and therefore prevents the use of 3D printers in education. 3D printing in the school environment is one of the innovative ways to make study more attractive and how to help make teaching more efficient. Technological progress is increasingly advancing in science and technology in creating new products in the automotive industry. Nowadays, technologies are becoming more and more popular, so why not take advantage of the opportunities that bring us today. In a few years, the connection of traditional teaching in connection with technologies and specifically with 3D printing will be a common part of teaching. Within the education in the automotive industry, a department focused on 3D technologies will be created over time, which would develop knowledge about 3D printing in children and prepare them for news and application.

1.4 Possible development of the student's ability in preparation for practice

The automotive industry faces different demands on all fronts: the demand for newer and more powerful vehicles, as well as the need to optimize production and streamline supply chains and logistics. One of the technologies that helps meet these challenges is 3D printing. Industrial 3D printing, in other words additive production, is increasingly used in several areas of the automotive industry.

3D printing technology brings several possibilities, from the production of rapid prototypes to the increasingly widespread production of spare parts or interiors. The inclusion of additive production can have a positive effect, for example, in vehicle development and production. It offers fast availability of components, their flexible construction and the possibility of producing components without demanding tools.

3D printing components are used on the vehicle body and in the passenger compartment, and can be characterized by high functionality and strength. Metal parts are produced by laser melting. In production, metal components made by 3D printing are added to vehicle bodies using an almost fully automated process.

The stage in which additive production can be used in the production of components is identified at an early stage in the development of automobiles. Both designers and experts research hundreds of components, focusing on the economic benefits of the new technology and the weight and shape advantages it brings compared to conventionally manufactured components.

Components for 3D printing are selected on the basis of several criteria and requirements, which are then translated into machine language.

Components that could not be manufactured before are created using generative design, which uses computer algorithms to rapidly develop components. Experts and computers work together to create components that can make the best use of materials in production. Several uses are only possible on the basis of generative design and 3D printing technology, which are suitable for creating demanding shapes and structures. Such that it was not possible to produce with conventional methods and tools.

Generative design shape-optimized solutions, while form and function have improved significantly. The components are approximately 50% lighter than comparable conventional components. As a result, they can make the best use of available space, as in the case of the boot lid strut.

The world's car manufactures incorporated HP Metal Jet 3D printers into their long-term design and manufacturing plan in 2018. The result of the cooperation between HP and Volkswagen is the possibility of fast volume production of custom components, personalized key rings and labels with the names of model lines. However, the cooperation does not end here. Their long-term production plan takes into account HP Metal Jet technology in the production of more stressed functional parts with demanding design requirements, such as control lever heads and rear-view mirror mounts. With the entry of electric cars into large-scale production, HP Metal Jet is expected to find further use, for example, in lightening metal parts with safety certification.

One car consists of six to eight thousand parts. The great advantage of additive technology like HP Metal Jet is that you can make many of these parts without having to build production tools first.

By shortening the production cycle, we can process a larger volume of parts very quickly. That's why the new HP Metal Jet platform for the entire industry is a huge leap forward, raising the bar a bit higher again and offering customers better products and innovations.

According to Martin Goede, head of technology planning and development at Volkswagen, "Our vision for the industrialization of additive manufacturing is fast becoming a reality with HP Metal Jet and changing the game for the automotive industry. HP's pace of innovation and advanced technology capabilities have exceeded our expectations. We achieve our goals and actively identify and develop functional components for production. "

We are still a long way from the full production of 3D cars, but their manufacturers are gradually setting milestones that contribute to achieving this goal. The example of BMW and Volkswagen is clearly not the only one on the market. Who knows where we're going in a year. Now it is only the tiny steps that improve the production process.

2 PRINTER PARTS

2.1 Mechanical Parts

2.1.1 Extruder

For many, 3D printing is a desktop machine that utilizes a process called as Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM) depending on different approaches to 3D printing.

Generally, FDM involves extruding a thread of material over a metal block through a nozzle. The extruded filament is melted, and the movement of the printer gives the material its shape. This process is repeated until the shape of the 3D project is created.

The melting and extruding of the material take place through a number of complex parts of the 3D printing machine known as the "extruder". The extruder allows for the process mentioned above develop through the use of parts in a specific sequence to extrude the plastic material.

The extruder is, for many, considered as the most important part of the 3D printers, as it transfers, melts and extrudes the material layer by layer onto the print bed. The extruder has different parts used for the handle of the moving and the processing of the plastic filaments. These parts, in a nutshell, can be separated into two: The cold end and the hot end.

The cold end: This part is the upper part of the extruder and consists of an extruding motor, toothed gearing, spring loaded idler and PTFE tubing. Here, the filament is fed and transferred to the hot end (the lower part of the extruder).

The motor of the cold end controls the motion of the filament, while the toothed gear on motor transfers the movement. The spring-loaded idler maintains the pressure on the filament and the PTFE tubing guides the filament to its destination.

The hot end: The hot end of an extruder is where the pushed and transferred filament ends up for the extrusion process to produce the end-product.

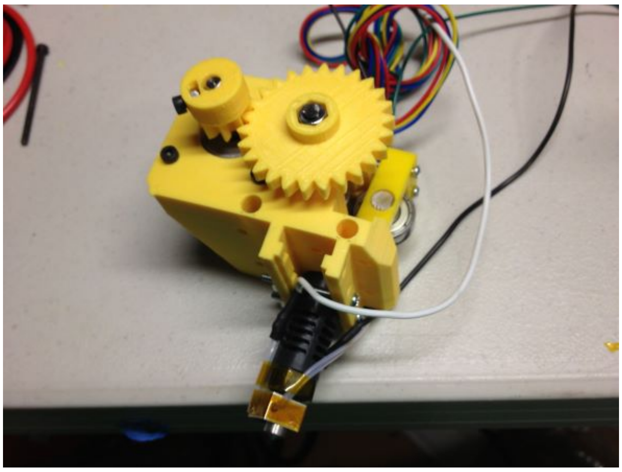


Figure 2-1 – FDM printer extruder

2.1.2 Print Bed

A print bed in a 3D printing machine is the surface where the printing and shaping process happens. In order to successfully complete the 3D printing process, the print bed should be flat and levelled. Usually, print beds are made out of plastic, aluminium or glass materials. In addition, print beds are sometimes lined with adhesives for better results. Therefore, adhesion along with the releasing of the material from the print bed when the cooling is done, are crucial properties of the 3D print beds.

Adhesion is important in determining the stability of the first layer and it has a significant impact on the success of the printing process. If the first layer is not sticked thoroughly to the bed layer, this will affect the placement of the other layers, resulting in an unsuccessful or low-quality end-product. Also, in the case of uneven cooling of the different layers and parts of the printed product, some parts of the print might be warped. Heat beds, in those cases, manage the cooling process and keeps the adhesion consistent to prevent warping.

Releasing of the product from the print bed after the cooling is also important, as it can result in broken or damaged end-products in the case of an uneven cooling or adhesion. Thus, the use of fine-tuned adhesives tailored for 3D printing that allows for easy detaching is important.

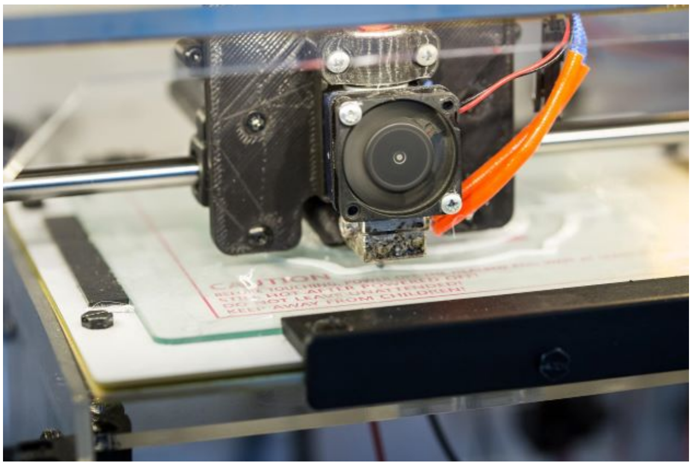


Figure 2-2 – Adhesion on print bed

2.1.3 Hot ends

As explained above, the hot-end is a component of extruders in 3D machines. Unlike many other component of 3D printing machines, a hot-end cannot be 3D printed and require a high-level of -calibration. The hot-end is where the pushed and transferred filament ends up for the extrusion process. In the hot-end, the filament is transferred into a heating chamber and liquefied. After this, the melted filament goes to the nozzle of the 3D printing machine to be extruded. The nozzle is an important part of the “hot-end” as this is where the filament comes out to be shaped. The nozzle is a small piece with a hole, and they are mostly interchangeable. Nozzles may be of different sizes, but the normal size is 0.4 mm.

Figure 2-3 – Extruder Hot-end

There are two types of extruders, namely Direct Extruders and Bowden Extruders depending on the linkage of the hot-end to the cold-end.

In Direct Extruders, the two parts of the extruder- the cold-end and the hot-end are basically attached together, and the filament goes directly from the cold-end to hot-end to be extruded. This allows for a direct path in the extrusion way and allows for clearer prints with less oozing. However, there is a chance that the filament might stick around the nozzle and cause damages to the hot-end of the extruder.

In Bowden Extruders, the cold-end and the hot-end are located separately in the extruder and linked with a tube. Bowden Extruders allow for a faster and more accurate 3D printing; however, Bowden Extruders tend to have retractions and more stringing than Direct Extruders.

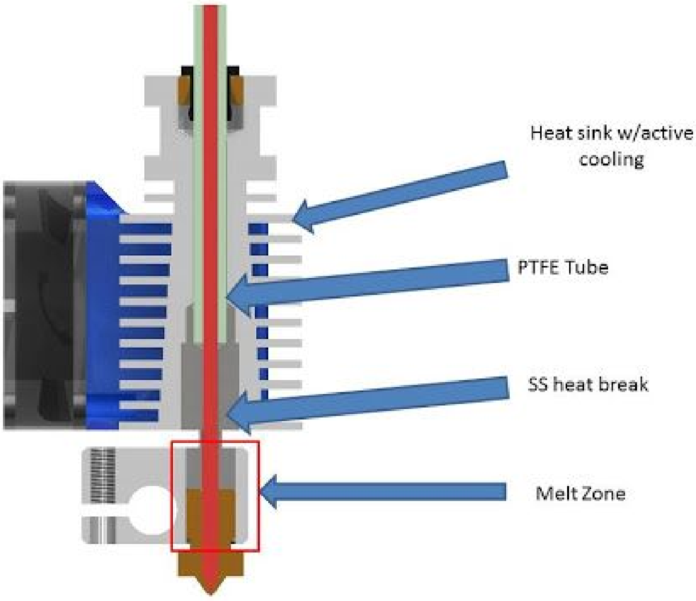


Figure 2-4 – Bowden Extruder

2.1.4 Filaments

Filaments, or 3D printing filaments, are materials used for fused filament fabrication modelling (FFF) of 3D printers. There are many different types of filaments with different properties that require different printing temperatures. Usually, filaments are available in 1.75 mm or 2.85 mm of diameter. Even though powder and resin are also used for 3D printing materials, the filament is the most common material used in 3D printers. Filaments are produced as slender plastic threads 100 meters long and circled into a reel for storage and printer feeding.

During the printing process, the filament if transferred to heating chambers in the extruder where it is then heated and melted. Then it is extruded via a nozzle while the extruder is moving around on the print bed to create the desired object layer by layer. Even though single extruder 3D printers are commonly used, there are also double extruder models that are able to create objects in different colours with different filament types.

Most common filament types used in the market are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) filaments. Most of the 3D printers available on the market are designed to use either PLA or ABS, even though there are complex and high-level 3D printers utilizing different sorts of filaments for different purposes.

Products printed with ABS filament are durable, tough, and non-toxic. ABS has a relatively higher melting point compared to others changing from 210 degrees to 250 degrees Celsius. If non-heated print bed is used in the printing process, there is a chance that the corners of the object printed can curl upwards in ABS filament. In addition, ABS can emit an unpleasant smell during the melting process, thus it is suggested to use a closed-frame printer in a well-ventilated room.

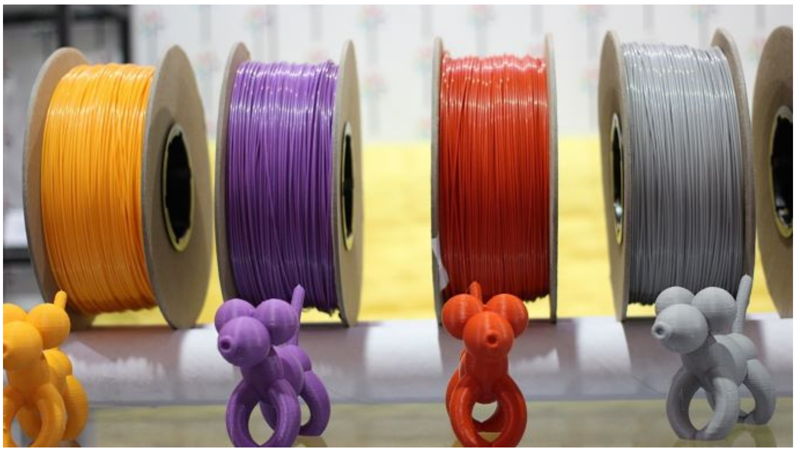


Figure 2-5 – Filament spools

PLA, on the other hand, has a lower melting point compared to ABS, ranging from 180 to 230 degrees Celsius. PLA is a biodegradable filament, and it is tougher than ABS in the sense of sturdiness and durability. PLA is generally easy to work with and causes jams in the extruders much rarer than the others. PLA is used as base material for composite and exotic materials.

In addition to PLA and ABS, there are other thermoplastic filaments that are used in 3D printing processes. Nylon is one those filaments that is used in 3D printing with a melting point at around 240 degrees Celsius. Nylons also have a tendency to warp after the printing process which can be avoided using a heated bed.

For printing more flexible objects, users can use TPEs (Thermoplastic Elastomers) that provide high elasticity to the objects.

There are also composite filaments that have PLA mixed with particles, powders and flakes of other materials. These materials can range from wood blends to sandstone, limestone or metals, aluminium, bronze or copper. These filaments share some of the properties of the mixed materials that they are mixed with. However, composite materials are relatively costlier than their non-composite counterparts.

2.1.5 Gears

Gears are used as a control mechanism for the amount of filament reaching up to the hot-end of the extruder of the 3D printing machines. The hobbed gear system controls the surface area that the filament touches, thus limiting the amount of force applied onto the filament. Also, there are geared extruders used in 3D printing machines that use gearing to alter the torque applied to the filament that allows for more power use with lighter and weaker stepper motors.

Figure 2-6 – Movement gears

2.1.6 Heater Cartridge

A heater cartridge is a resistive heating element that is tube-shaped and used in 3D printers. Its function is to convert electric current into heat. In 3D printers, heater cartridges are used to melt plastic filament in the hot-end.

Heater cartridges generate heat as an electric current passes through them. They are basically big resistors that are shaped to be installed in industrial equipment and 3D printers.

On the micro-level, when energy in the form of electrons move through the resistor, they bump into its structure. As they do this, they lose some of their energy in the form of heat.

The higher the resistance of the resistor, the harder it is for electrons to get through. On the other hand, if there are a lot of clean paths for the electrons to pass through, the resistance is low. Not only do heater cartridges come in a variety of wattages, but they also have a voltage rating attached to them. Typical wattages for hot-end heater cartridges are 25W, 30W, 40W and 50W. But can be found as low as 20W and as high as 60W, and even 80W for a SuperVolcano hot-end. Their labelled voltages are nearly always 12V and 24V because those are the voltages that typical 3D printers run on.

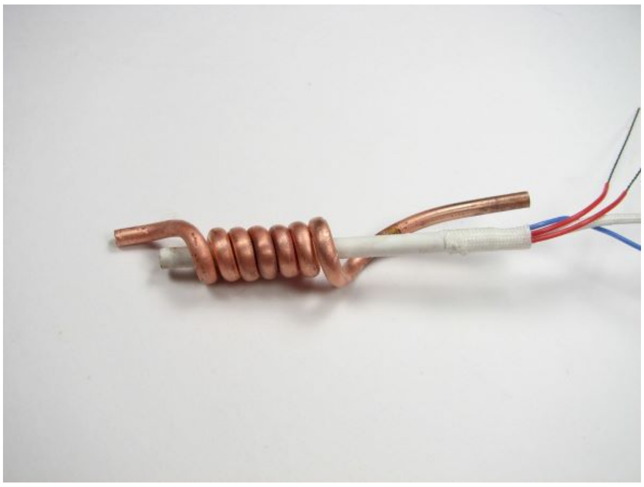


Figure 2-7 – Heater resistance

2.1.7 Thermistor

A thermistor is a device used in 3D printers to measure the temperature. For successful printing processes, controlling the temperature of the nozzle and the heated bed is highly critical. A number of sensors can provide this data, such as thermocouples, resistance temperature detectors (RTDs) and others. However, thermistors (Thermally Sensitive Resistors) are mostly used in 3D printers as they are simple, cost-effective, and highly integrated with the controller boards in 3D printing machines.

Thermistors are found in several locations within a 3D printer. Typically, in the hot ends the nozzle is located in a metal block which melts the filament. Connected to this block are two wires, one of which powers and heats the block while the other is connected to the thermistor inside the metal block that measures the temperature of the nozzle.

On the heated bed, the thermistor is located between the print surface and the heating element of the bed.

In any case, the thermistors are connected to the controller board, which is detected and mapped out by the firmware of the 3D printer for the calibration of the machine.

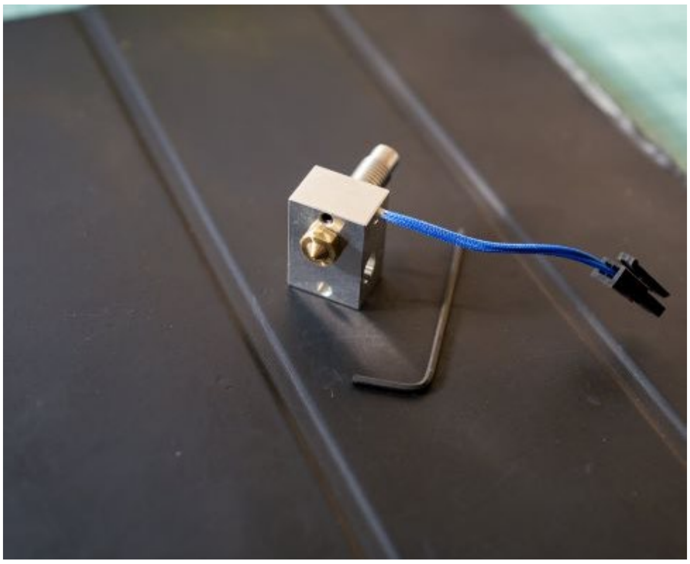


Figure 2-8 – Extruder and nozzle

2.1.8 Nozzle

The nozzle is the part of the extruder that extrudes the filament. It transmits the thermal energy generated by the heating cartridge and metal block to the filament and melts the material. There are three major features that are integral to the design of the nozzle: the size, material, and inner diameter.

The bigger the nozzle, the more mass and surface area available for transferring heat to the filament, thus rendering this process more effective and capable of higher extrusion speeds. Thermal transfer also relates to the nozzle material, as each material conducts energy differently based on its properties.

Lastly, the inner diameter of the nozzle affects the amount of plastic extruded per second, a property known as flow, which also determines the maximum extrusion speed. The inner diameter also relates to final part accuracy: smaller diameters allow for thinner layers and walls to be printed.

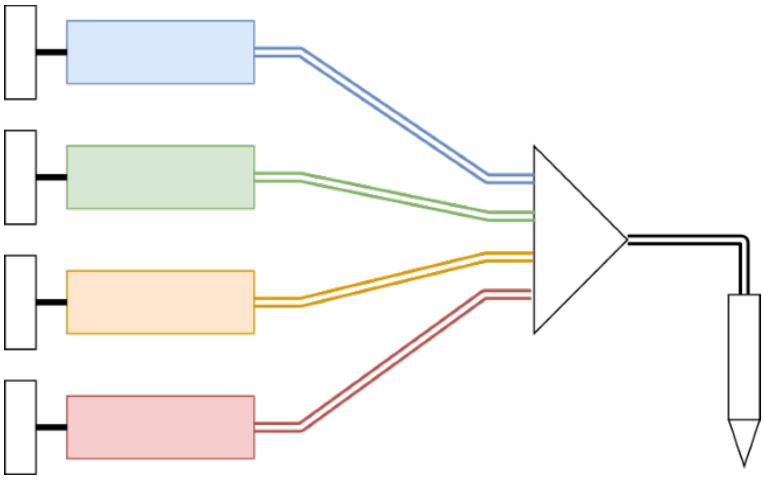


Figure 2-9 – Multi-filament nozzle system

2.1.9 Cooling Fan

There are 5 areas in 3D printers that cooling fans are used in:

- Control board: Fans in control boards are used to cool down the main circuits of the 3D printer, i.e., the motor drivers and the processor. Keeping these components at low temperatures is crucial for the lifespan of the printers.
- Hot End: Cooling fans will be located around the cold end close to the hot end, to keep the temperature of the hot end low. These fans are used the keep everything cool except for the heater block and the nozzle.
- 3D prints: Some parts of the cooler fans in the 3D printers are used to cool down the objects that are freshly out of the nozzle, by blowing a stream of cold air onto objects.

- Power Supply: Cooler fans are also used to keep the temperature in transistors, resistors and power transformers in 3D printers to avoid overheating
- Motor: Even though not much common, in some 3D printers, cooling fans are used in stepper motors to cool off in order to keep them at optimal functioning temperature.

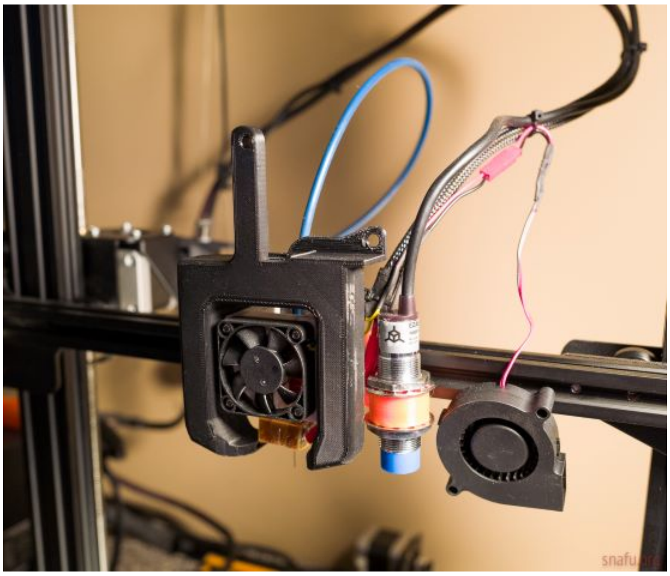


Figure 2-10 – Cooling fan system

2.1.10 X-Y-Z Axis

The X-Y-Z axis in 3D printing machines refers to overall operation of the extrusion of layers in the X, Y and Z axes. Depending on the machine, only one, two or three axes can be moveable to create the object.

The 3D printers using the X-Y-Z axis are known as Cartesian 3D printers and are the most common 3D printers on the market. Based on Cartesian coordinate system, this system uses the three axes: x, y, and z as mentioned above to determine the direction of the extruder. Usually, with this type of printer, the printing bed usually moves only on the Z-axis while the extruder works two-dimensionally on the X-Y directions.

Even though it might be confusing to describe the movements in the axis, as for the operator facing the machine, X axis allows movement from “left” to “right” while Y-axis allows for “forward” and “backward” movement. Finally, the Z-axis allows for “up” and “down” movement.

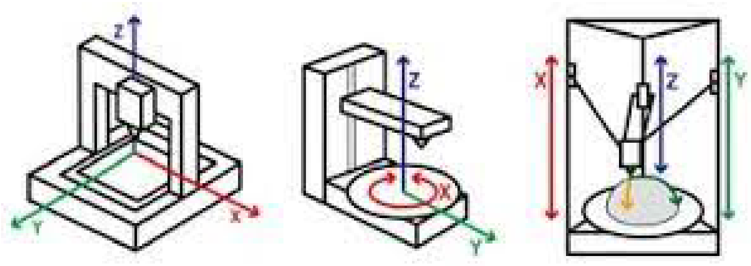


Figure 2-11 – Movement architectures

2.1.11 EndStops

End stops can be described as the electronic pieces located at the ends that axes connect to the mainboard. They are used to signify to the extruder where the end of the axes is so that the extruder wouldn't go off the limit of the 3D printer. This stops the object from derailing or jamming at the end of that axis. Endstop switches are the most common type, used especially by lower-budget machines. However, there are other types of endstops that are available, including optical and magnetic endstops. Different types of endstops have different strengths and weaknesses, depending on your necessary level of precision and the budget.

2.1.12 Lead Screws

A lead screw is a screw used as a linkage in the 3D printer, to translate turning motion into linear motion. Because of the large area of the sliding contact between their male and female members, screw threads have larger frictional energy losses compared to other linkages.

In 3D printers, screws are usually driven by the stepper motor and guided by the X and Y axes. Acme threads are connected to the carriage mechanism and all axes are started with a stepper motor-driven lead screw with and anti-backlash acme thread, and they move along the linear ball bearing guides.

One of the significant advantages of screw-rail configuration for linear motion controlling is that it requires a fraction of several components that are essential for belt-driven 3D printers and take shorter time to assemble

Compared to belt-drives, that produces linear motion with frequency of $\pm$0.1 mm/m and a layer height of 100 microns in 3D printing practices, screws offer linear motion with frequency of

± 0.02 mm/m and a layer height of 50 microns, making them a lot more precise and accurate for controlling 3D printer performance.

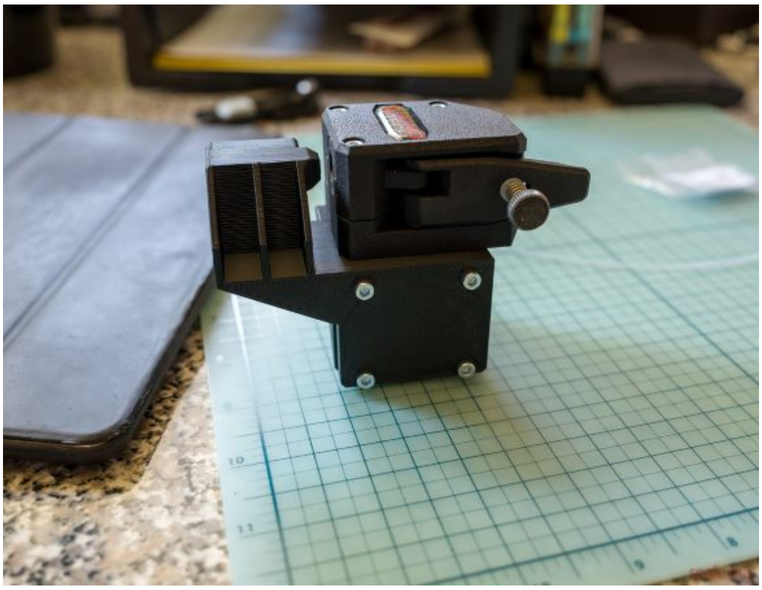


Figure 2-12 – Lead Screw

2.1.13 Belts

For obtaining good results, accuracy is important in 3D printing. If anything gets loose during the printing process, it will be clearly visible in the print. Therefore, 3D printer belts are used to make sure that the movements are controlled and accurate as much as possible. The use of stepper motors can help provide more advanced control, but it's useless if the belt slips.

That's why most 3D printer belts are designed to fit along gears, having many measured notches on one or both sides. A drive gear is attached to the stepper motor, and the belt fits into the notches of the gear, preventing it from slipping, and allowing it to rotate with the motor. To keep the belt tight, it can be fitted over another such gear, which acts as a pulley. This second gear is then attached to the printer's frame at the opposite side of the respective axis bar.

Various print elements are attached to the belt along its axis. When horizontal, an axis bar supports the weight of one or more printer elements, and the belt's only job is the move those elements along the axis. However, when set up vertically, belts are usually depended upon for support. Sometimes a counterweight is even added to the belt to keep the motor from having to work so hard.

Figure 2-13 – Belt and bush for axis movement

2.1.14 Stepper Motor

A stepper motor is an integral part of the 3D printing machine. Stepper motors are responsible for all linear movements made by the machine, for example, a change of position in the Y-axis is caused by a rotation in a stepper motor.

The difference between a general electric motor and stepper motors is that stepper motors selectively turn a certain percentage of a revolution, called steps, and can start and stop at will, which allows machines like 3D printers to achieve precise movements.

In any 3D printer, you'll find stepper motors attached to the X, Y, and Z axes. For X and Y they may use belts or screws to transmit the rotation into linear movement, and they typically use one motor each. On the Z-axis, you may find one or two, depending on your machine, and it (or they) will usually use a screw, as the Z-axis must carry the weight of the whole toolhead.

Additionally, in 3D printers, there's one more stepper motor: the one that controls filament extrusion. It's usually attached to a system composed of a spring, a pulley, and a gear, all of which together make the filament move. You don't use one for spindles on CNC machines as they need a much higher torque, greater speed, and come with their own integrated electric motor.

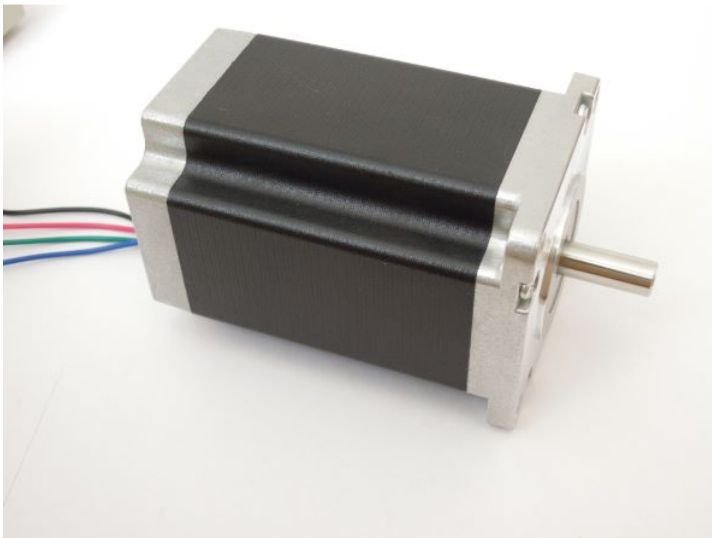


Figure 2-14 – Stepper Motor

2.2 Electrical Components

2.2.1 Power supply

Power supplies, or Power Supply Units (PSU) are generally metal boxes with terminals or a bundle of wires at one end and a fan on the side. PSUs usually contain a transformer (or a series of transformers), which receive the 110 to 240 volts from the wall and lowers them to a more reasonable 12 to 24 volts. Also, within a PSU is a rectifier circuit, which converts the wall's AC current to the DC current that a 3D printer needs.

The hot-end of the 3D printer is an important factor in the voltage of the 3D printer. Hot-ends are typically 12 or 24V configurations, thus it is important to check the voltage of the hot end before deciding on the power supply. It may require a step-down converter and some MOSFET transistors to interface with your control board but ideally it will match the hot end's voltage.

Figure 2-15 – Power supply

2.2.2 Motherboards

All the electrical units in a 3D printer are connected to the motherboard where microcontrollers are located in within a 3D printer. Microcontrollers implement the codes sent from 3D printer software and enable the production of the 3D printed objects. This process not only includes ordering and sequencing the time and the direction of the movements of the stepper drivers and the motors, but also controlling of the data coming from various sensors from across the device such as the temperature and the state of the limit switches. The motherboard provides and ensures smooth communication between the input and the desired output. Motherboards usually have the following features: 24V input voltage, 32 Bit processor, Internet connectivity, spare IO bins. 24v input voltage allows for higher motor performance while 32 Bit processor allows for more complex tasks to be fulfilled. Internet connectivity, on the other hand allows for remote production of 3D products while spare IO bins would allow higher customization and quality of the products printed.

2.2.3 SD Card Slots

While USB drives are used in many of today´s devices, 3D printers usually utilize SD card slots. This is mainly due to the fact that SD cards are easier to implement compared to USB drives in terms of hardware and software characteristics of 3D printers. Additionally, USB drives usually require extra hardware to make them readable by the 3D printer. The printer will also need a software driver that lets it access that information. Therefore, SD cards are much more convenient and frequently used storage and external data transfer method in 3D printers.

2.2.4 Stepper Drivers

Stepper drivers control the movement of the stepper motors, triggering them to coil and making the shaft of the stepper motor circle in the precisely controlled and expected manner. Some motherboards have the stepper drivers integrated within the board, and some have them as replaceable plug-ins.

All stepper drivers have a central chip that processes inputs and outputs as movements across each axis. Nema17 stepper motors have a certain number of steps per rotation (with most being 200) which is just how many changes in the magnetic field of the coil it will take to completely rotate the motor shaft. By carefully controlling the current that the driver outputs, it will magnetize one side of the motor, causing the shaft to spin, and by constantly and consistently changing which side is magnetized is how the motor spins.

Drivers can also do something called “micro-stepping” where instead of moving strictly one tooth of the gear or step at a time, the driver can apply just enough current to hold the gear between steps, increasing the accuracy of the output motion. As of today, 1/16th of the micro stepping is fairly standard, and has been for a while, but there are some drivers that can go to 1/32, 1/64, 1/128, or even 1/256 micro-stepping. The more micro-stepping that a driver outputs, the more current it will need to be able to have the torque to hold those fine positions.

Figure 2-16 – Stepper Motor driver

2.2.5 Screen and User Interface

The user interface in 3D printers is usually located on top of the printers, usually with touch screen feature nowadays. The user interface contains menus and submenus that allow the users perform a range of functions such as accessing the print platform, starting the printing process, putting the printer on standby mode, warming the printer, displaying the current materials' state, material information, etc. It also allows for troubleshooting, date and language, the overall printing data, and maintenance of the printer.

3 CREATION OF OBJECTS IN A VIRTUAL ENVIRONMENT

3.1 Introduction

This unit will focus on the creation of objects in a virtual environment. This is the first step to printing and giving the shape of what we need or want to create with our 3D printer.

In this course, until now, we have seen the principles of 3D printing and the main components of our 3D printer. The time has arrived to draw our parts and after that, to print and bring to life a real piece.

The creation of our sketch is perhaps the most important moment to reach success. One mistake in the sketch can be catastrophic for the correct behaviour of our piece.

After this unit, it's expected that the trainees can design and create pieces and parts on OnShape Software in a virtual environment and recognize the best practices to do that. At the end of this unit, the trainees are expected to:

- Know the main commands to design objects using OnShape;
- Be capable of creating a part/object on OnShape;
- Know and execute some drawing techniques;
- Recognize and understand the different file types generated and used in the creation process;
- Recognize and understand the functions of an STL file.

3.2 3D Drawing

But what is 3D Drawing?

3D drawing is the ability to draw shapes with height, width and depth. It's one of the most common techniques already used in civil construction, architecture and most recently in graphic design because this allows the professionals in these areas to have a more precise perception of the final result of their jobs. 3D drawings are usually made through computer control by 3D modelling software. After creating the design it's possible to use a 3D printer to create physical objects, by adding material layer by layer.

With the appearance of 3D printers, these techniques and knowledge have become more important for students, enthusiasts, shop workers and medical services.

By merging these two concepts, it's possible, for example, to do simple things like building a new toy, or more complex ones, like printing a new bone to be used in bone replacement surgery.

There's no limit to the potential of this technology, and only a full understanding and comprehension of these concepts will allow us to benefit from it.

3.3 OnShape Software

OnShape is one of the most popular professional CAD software-as-a-Service (SaaS), capable of developing 3D shapes, objects and forms, allied with many interesting features like built-in data management, real-time collaboration tools, business analytics and more.

With this software, we can create different elements, and objects with many shapes, formats or functions in 3D and when finished, it's possible to export them to an STL file.

Working on OnShape is the first step to creating our 3D printed object.

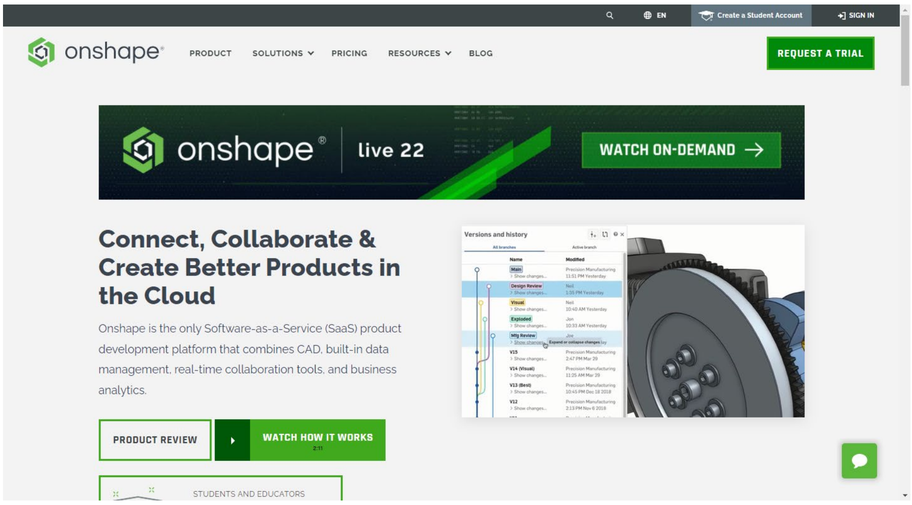


Figure 3-1 – OnShape Interface

3.4 Create a part/object on OnShape

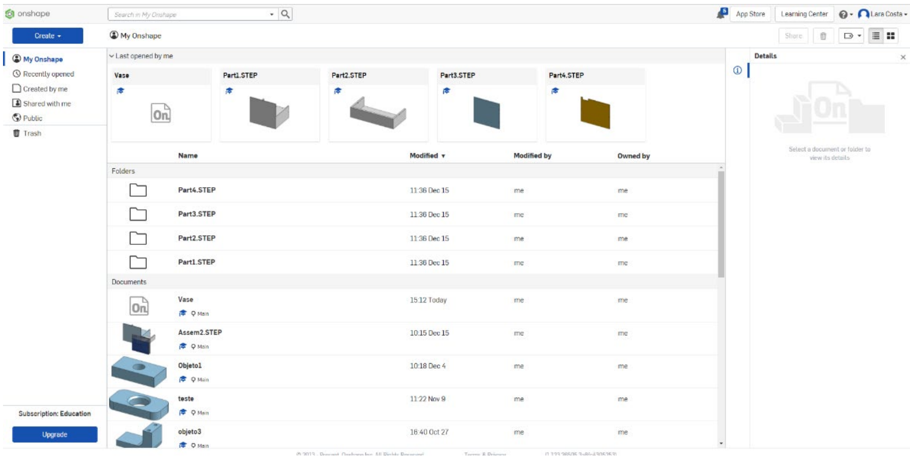
In the following pages, you will be able to follow a step by step process to design a 3D part in OnShape software. For this training unit, we will design a small identification plate with text on it, using the main and essential drawing tools.

Having mastered these tools, at the end of the training session you should be able to draw any piece with ease.

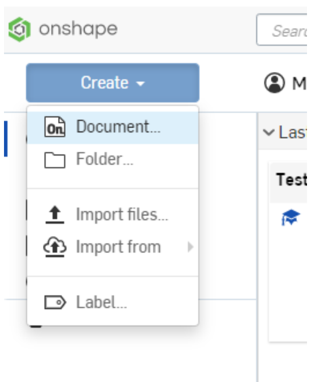
For complete mastery, this training session does not rule out the necessary training concerning all of the tools that will be used.

In the next steps, we'll see how to create a part/object using OnShape Software.

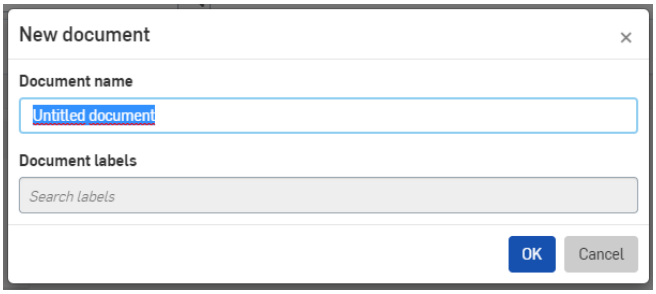
1st Step – Open OnShape and Sign In to your account.



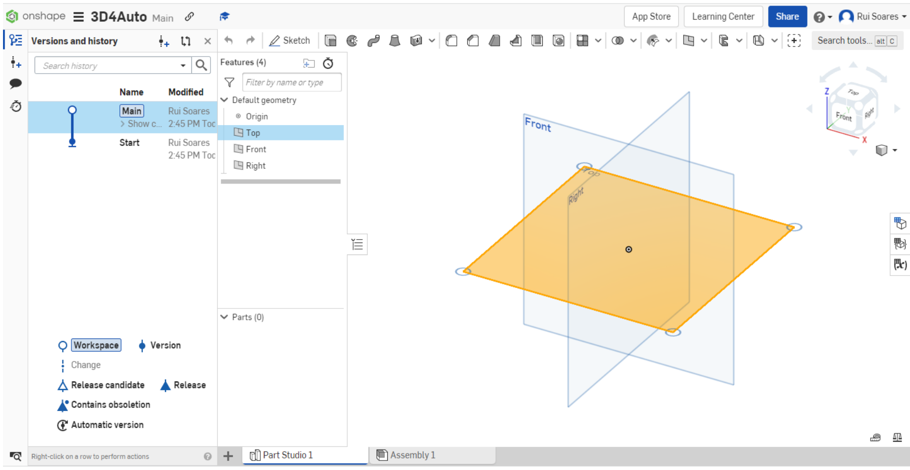
2nd Step – Create a new document.

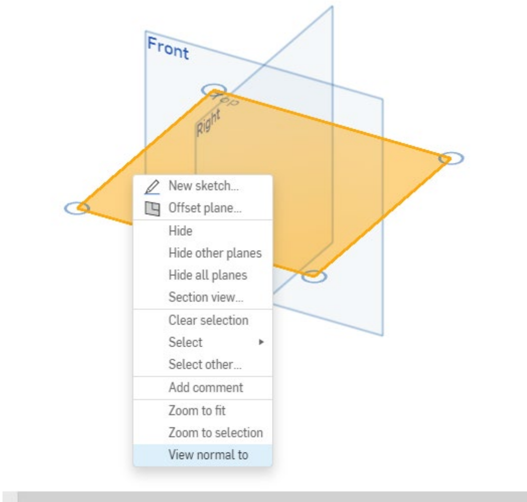


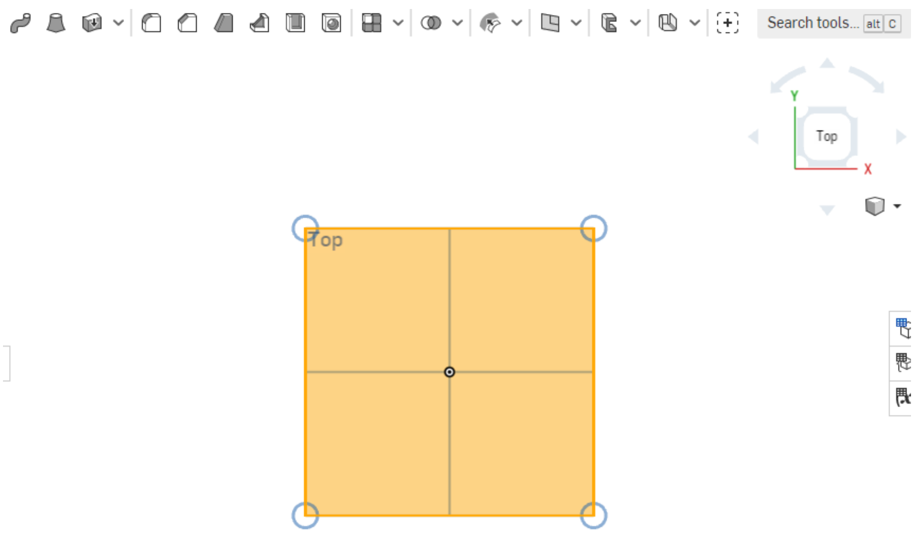
3rd Step – Give a name to your project such as “3D4Auto” or “Example”.



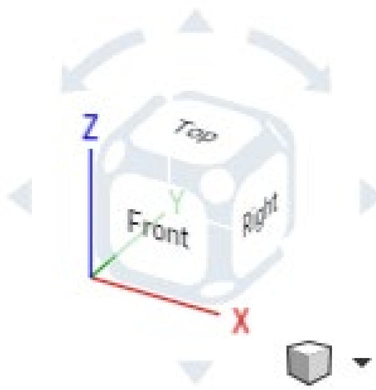
4th Step – Select the desired plan (in this case TOP) and with a right-click on it, select “View Normal to”.



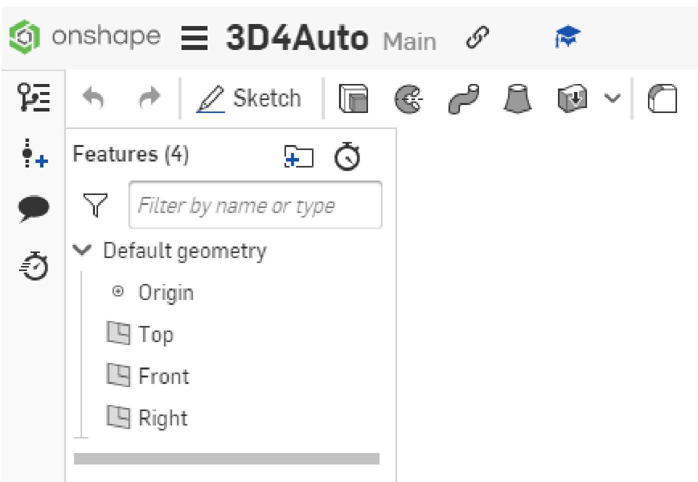




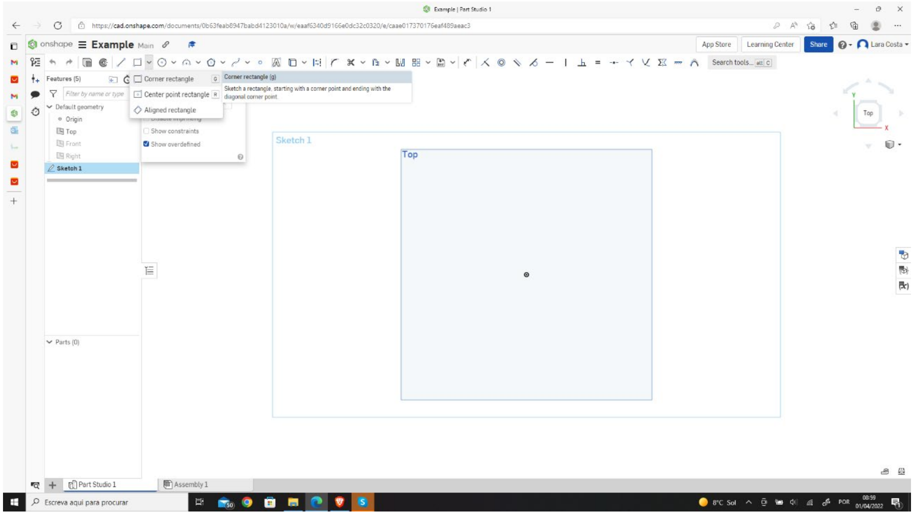
TIP: for faster access to a desired view, you can use the view cube in the top right corner.



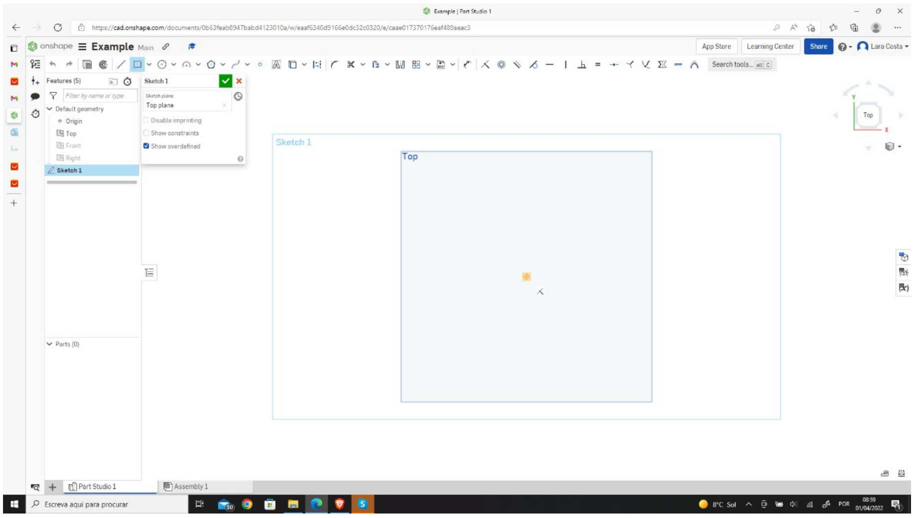
5th Step – Click on “Sketch” to unlock drawing tools.

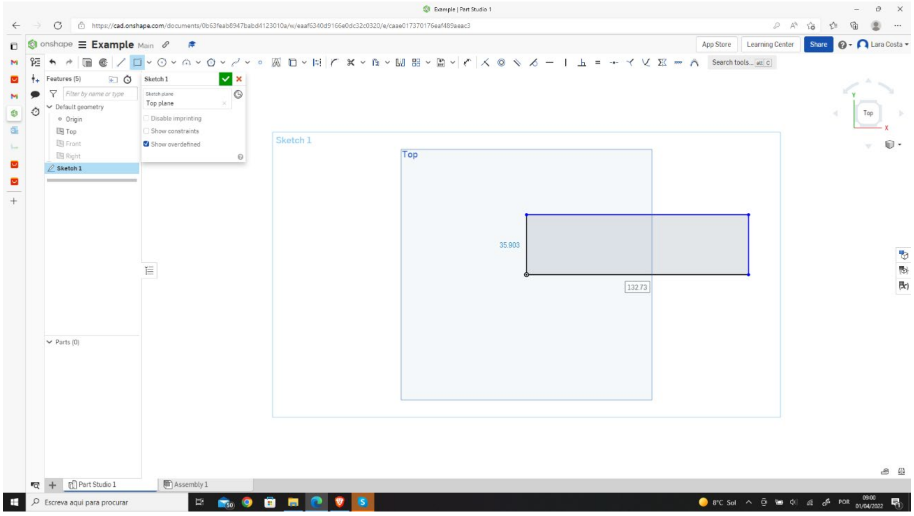


6th Step – Select "corner rectangle" to draw.

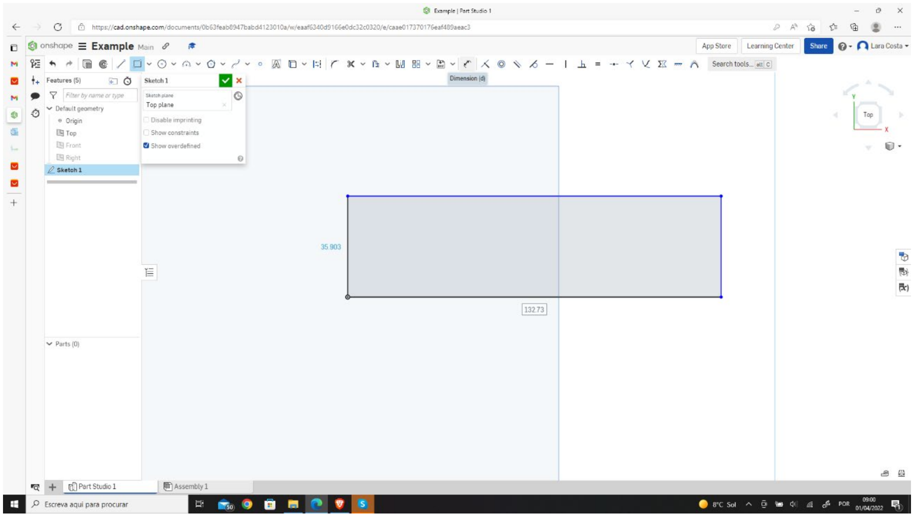


7th Step – Draw the rectangle starting on the center point.

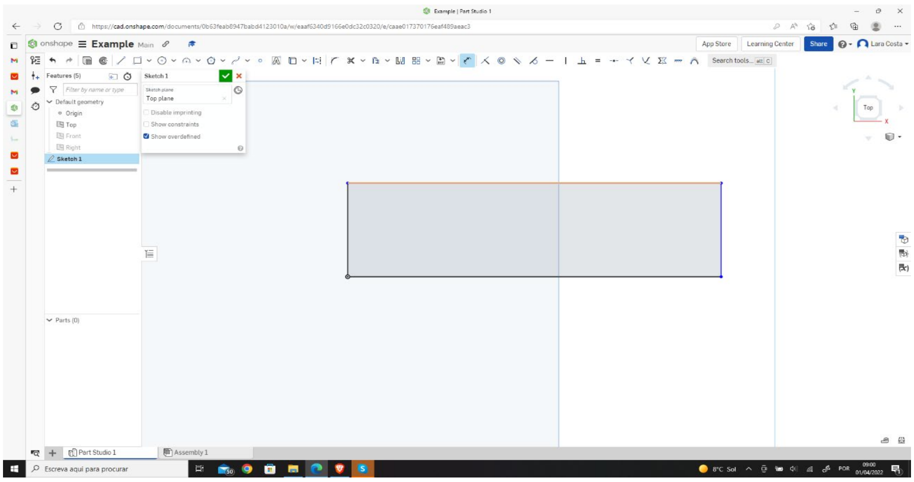




8th Step – Select "Dimensions" to set the measures of our rectangle.



9th Step – Select the TOP (or BOTTON) line and set the intended measure (100mm).



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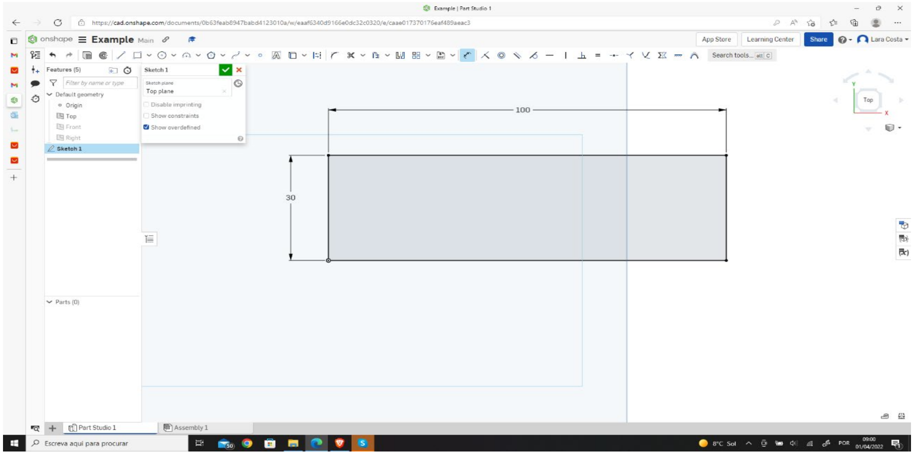
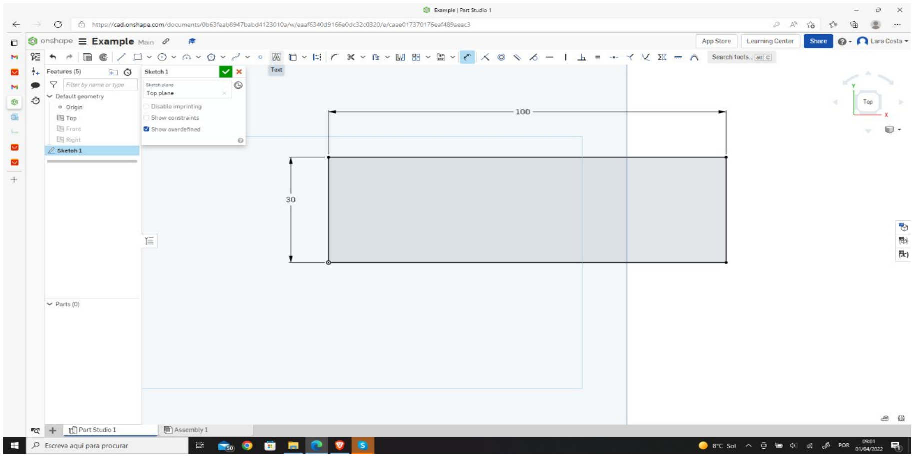
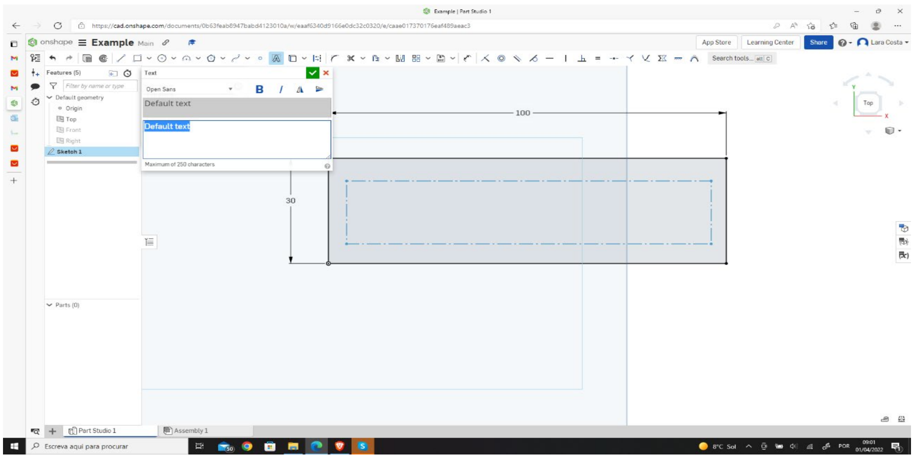
10th Step – Repeat the last process for the RIGHT (or LEFT) line and set the intended measure (30mm).



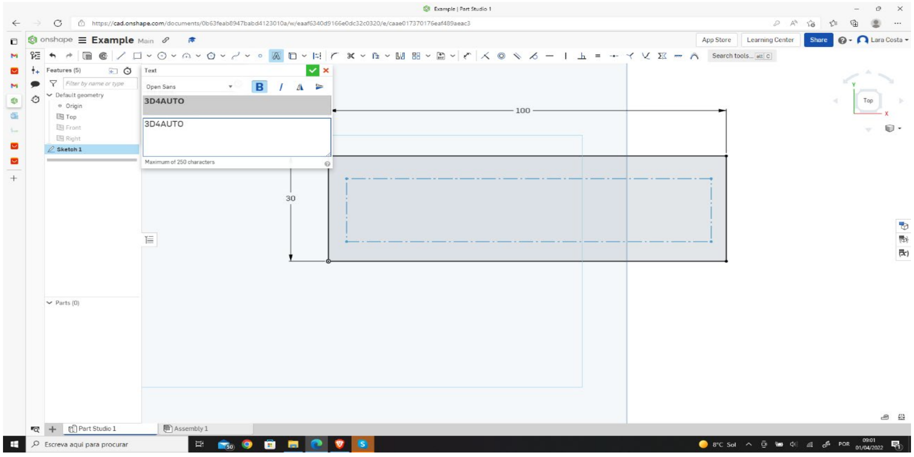
11th Step – Select the “Text” tool.



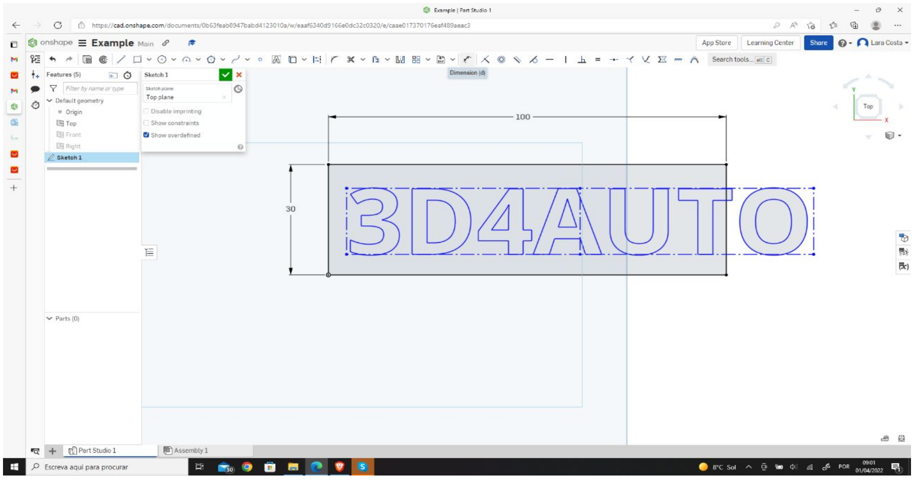
12th Step – Draw a rectangle inside of your first rectangle.



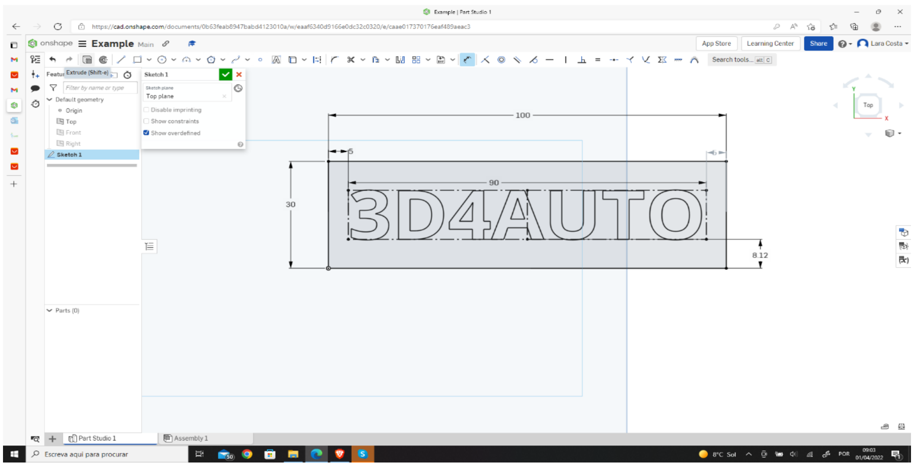
13th Step – Write the desired text (in this case it will be “3D4AUTO”), select the “Bolt” setting and confirm by clicking on the green check mark.



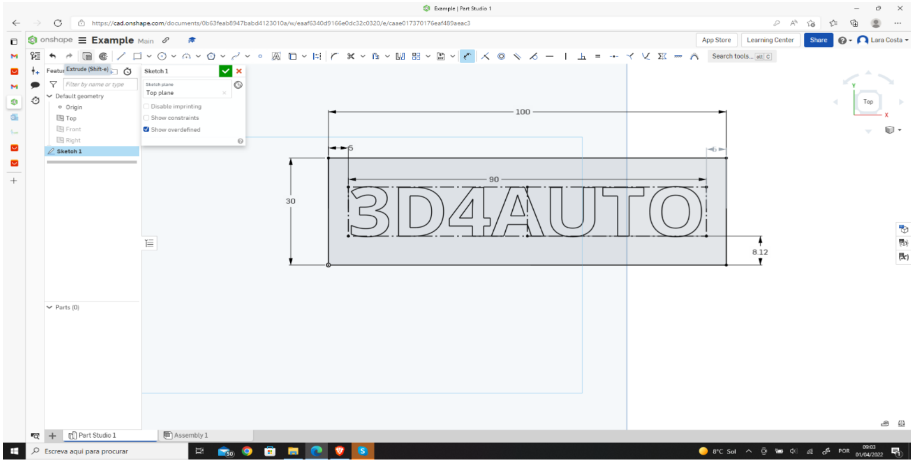
14th Step – Select the “Dimension” tool again.



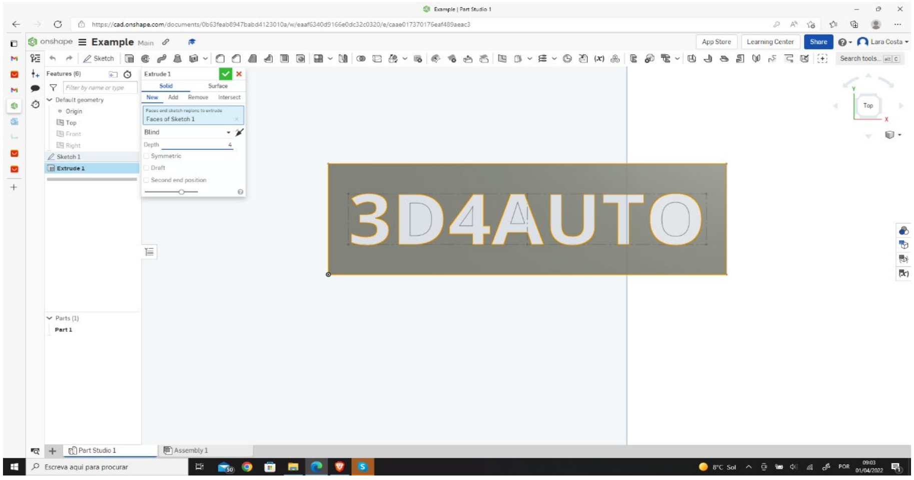
15th Step – Set the dimensions like in the following image to re-dimension and center the plate.



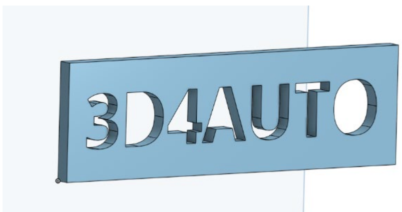
16th Step – Select the "Extrude" tool.



17th Step – Change the Depth to 4mm and confirm by clicking on the green check mark.



18th Step – Now you have finished the drawing



3.5 *Drawing Techniques*

Some of the more complex parts require the drawing of complex details. A good strategy is to think about whether that detail can still be drawn in the 2D plane. If possible, it is better to do so. The more details you implement in 2D, the easier it will be to achieve the desired result.

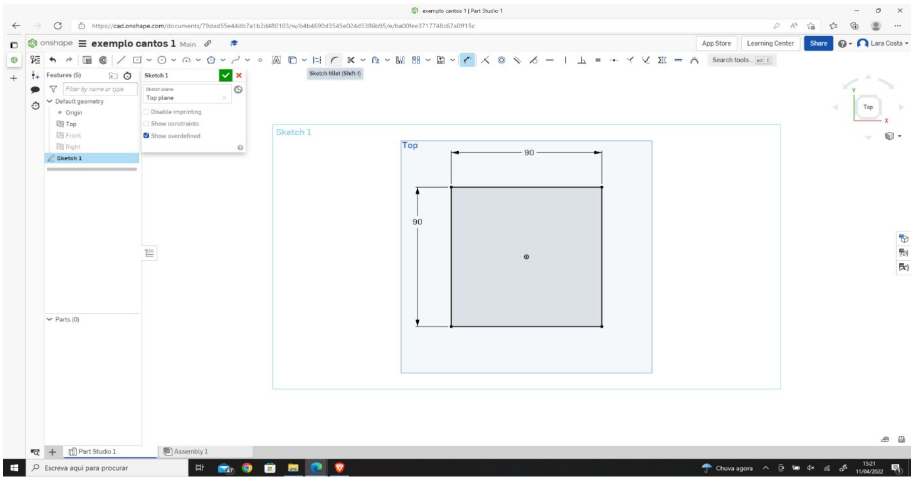
However, it is not always possible to include all details in the 2D plane. In that case, the detail can only be drawn after the drawing has been given volume.

In the next image, we can see two examples of both situations applied in the same piece, where the detail is applied in 2D and 3D for different situations.

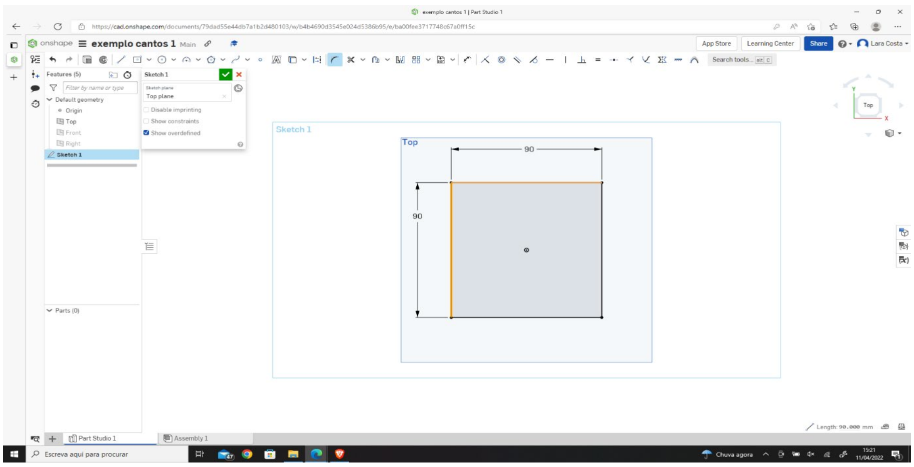
Mastering this concept is one of the most important drawing techniques. Whenever it is possible to draw the detail in 2D, it should be done!

3.5.1 Doing round corners in 2D and 3D drawings

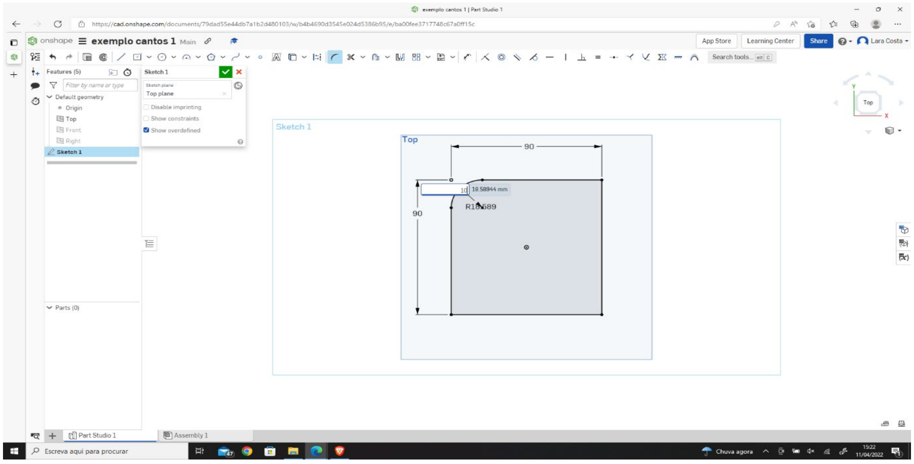
1st Step- Draw a rectangle such as the one in the example and select the "sketch filet" tool.



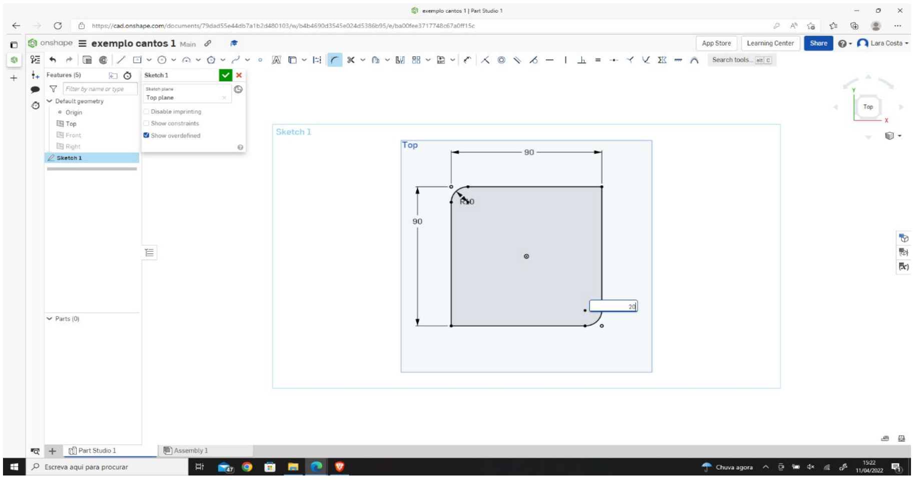
2nd Step - Select the two lines in orange.



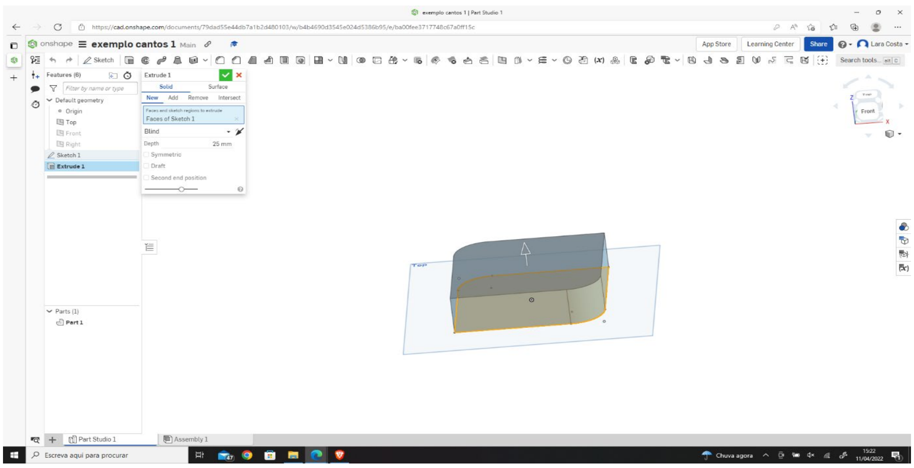
3rd Step - Set the radius measure (10mm).



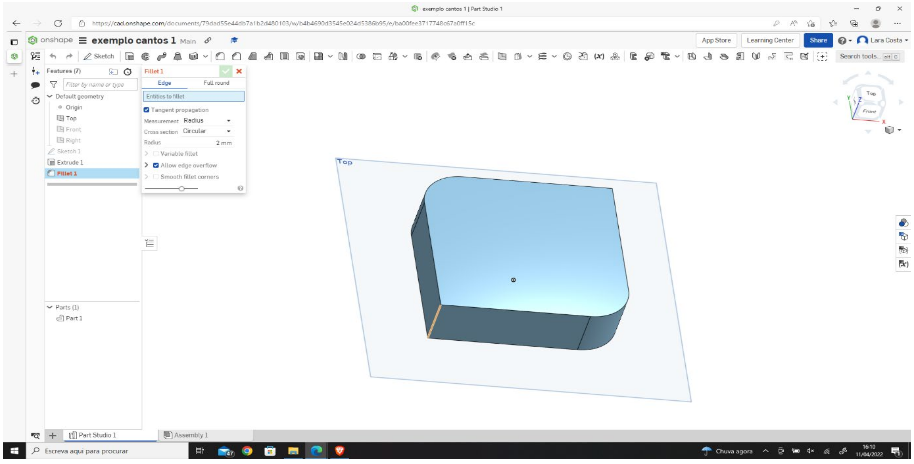
4th Step - Do the same (from steps 1 to 3) but this time set the radius measure to 20mm



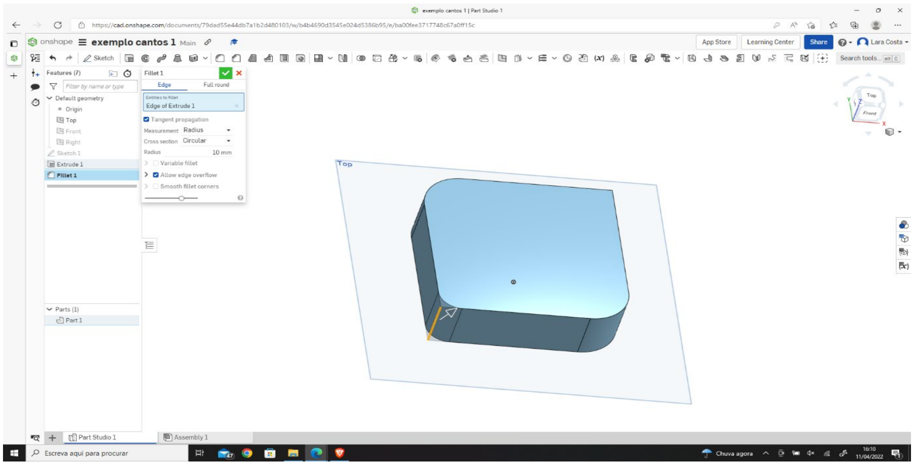
5th Step - Select “extrude”, set the depth to 25 mm and click on the green check mark.



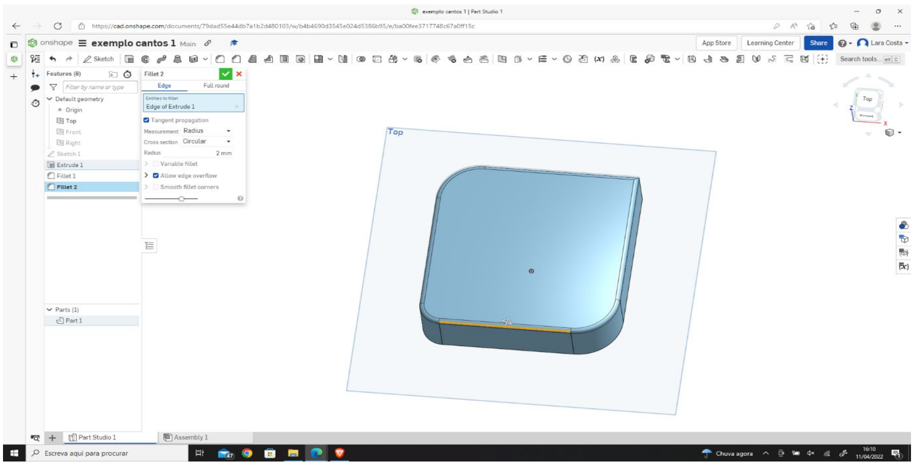
6th Step - To create the fillet in 3D, click "fillet" and select the edge, like in the image.



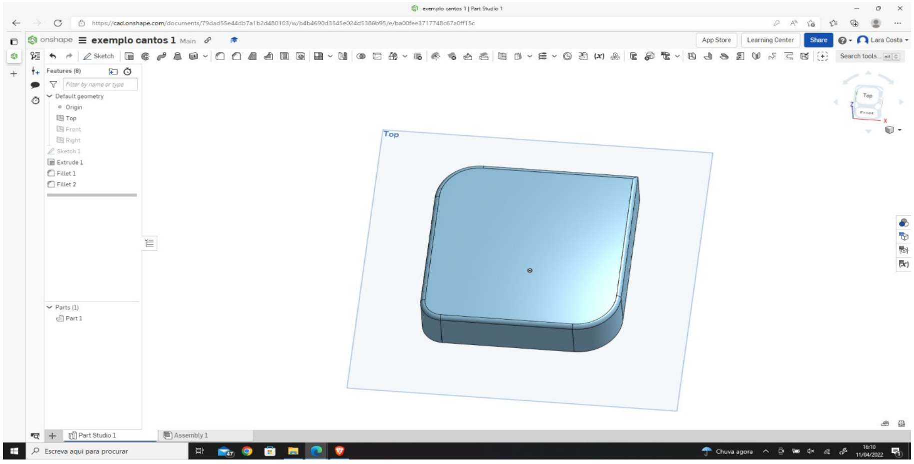
7th Step - Change the radius to 10 mm and click on the green check mark.



8th Step - Repeat the actions from steps 6 and 7, but this time set the radius measure to 2mm and click on the green check mark.



9th Step- This should be the final result.



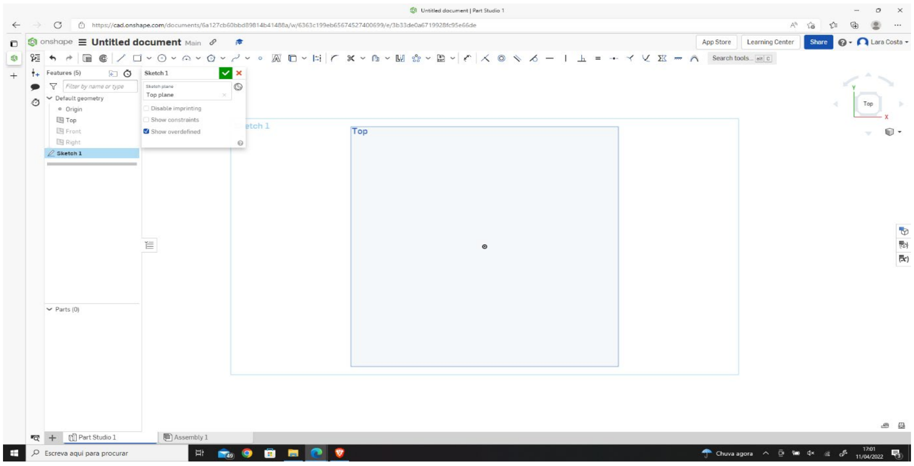
In some cases, we may need to repeat a detail in a pattern an x number of times. In these cases, it can be useful to know and master the "Circular Pattern" tool, which allows us to repeat a detail several times along a circumference.

This tool becomes very useful for drawing parts like gears or gearwheels, for example.

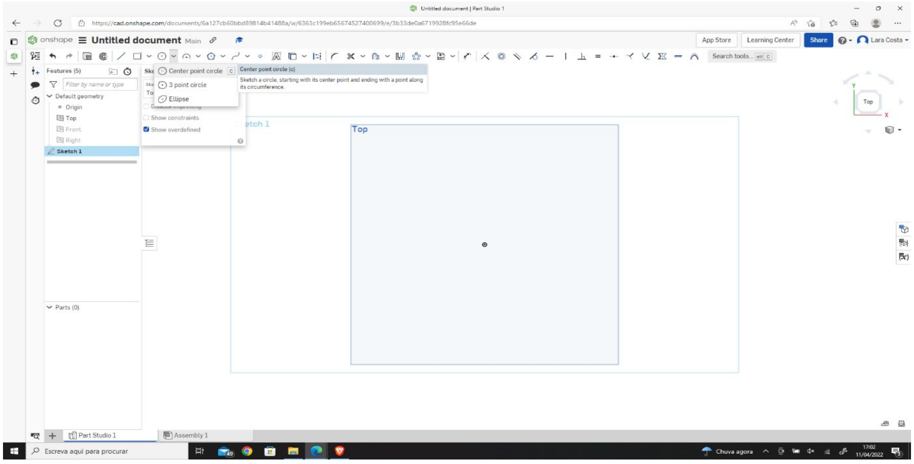
In the next few images, we will see an application of this tool to execute a detail repeated along the perimeter.

3.5.2 Circular Pattern Design

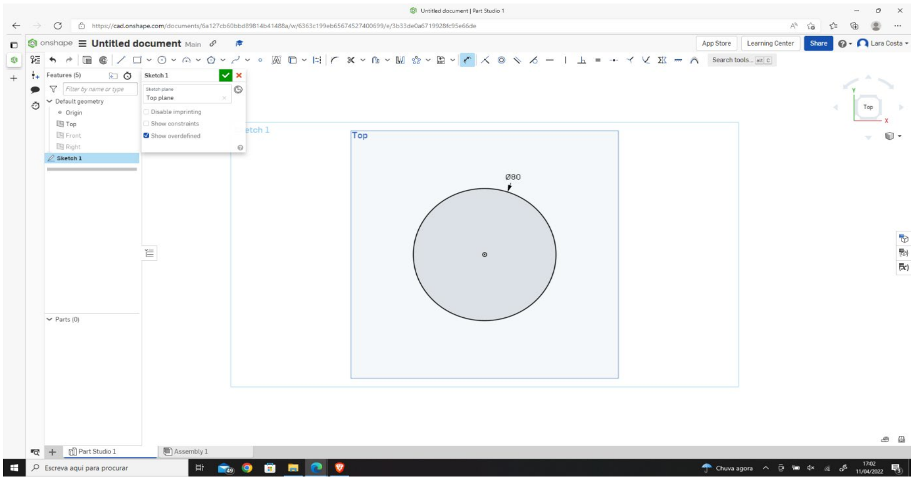
1st Step - Open the sketch.



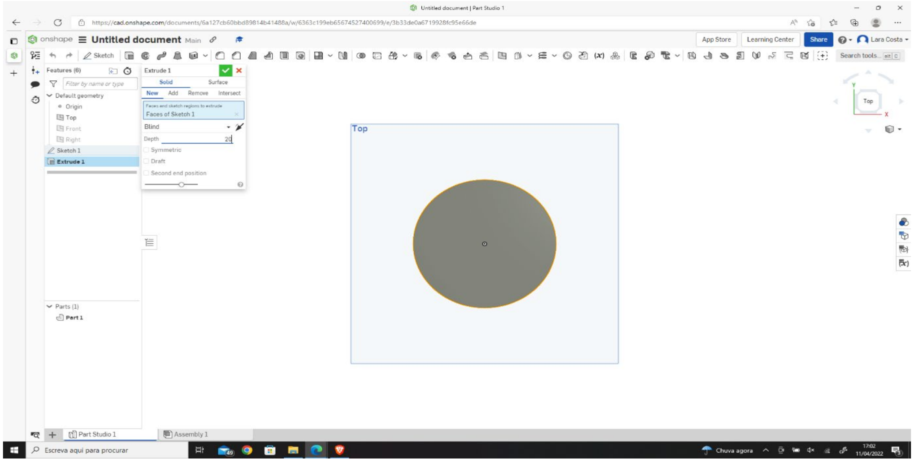
2nd Step - Select the "center point circle" sketch tool.



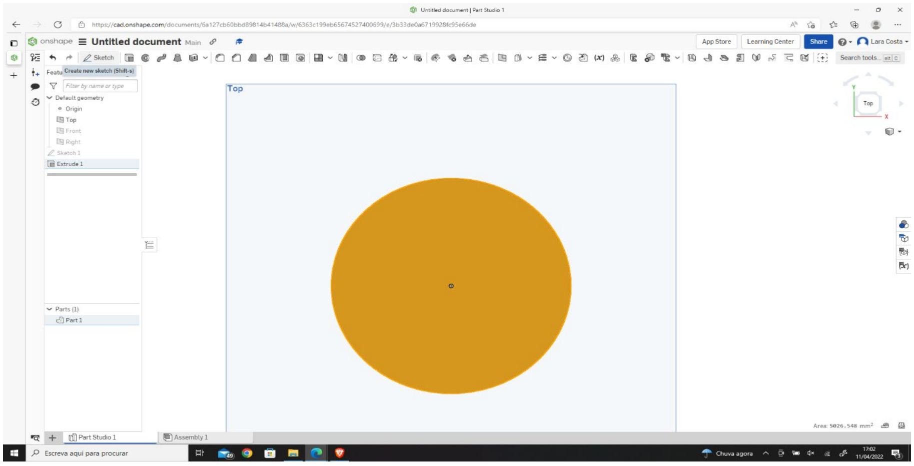
3rd Step- Draw a circle starting at the centre and set its dimension to 80mm.



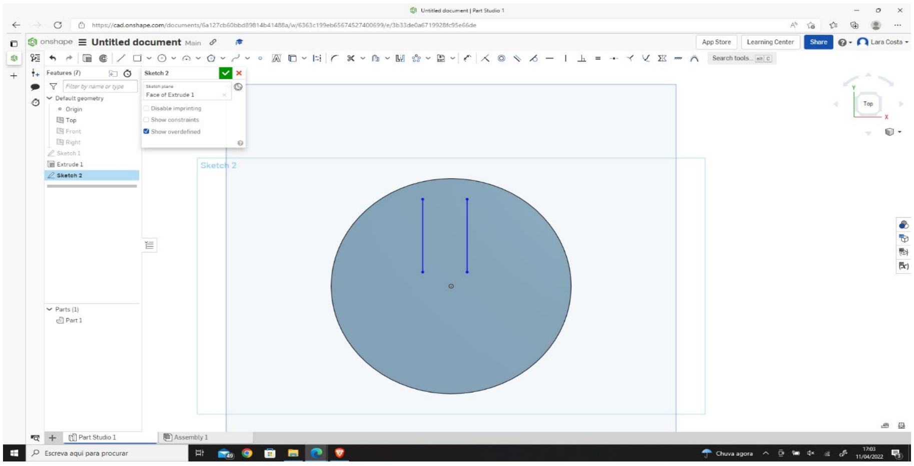
4th Step - Select the extrude tool, change the depth to 20mm and click on the green check mark.



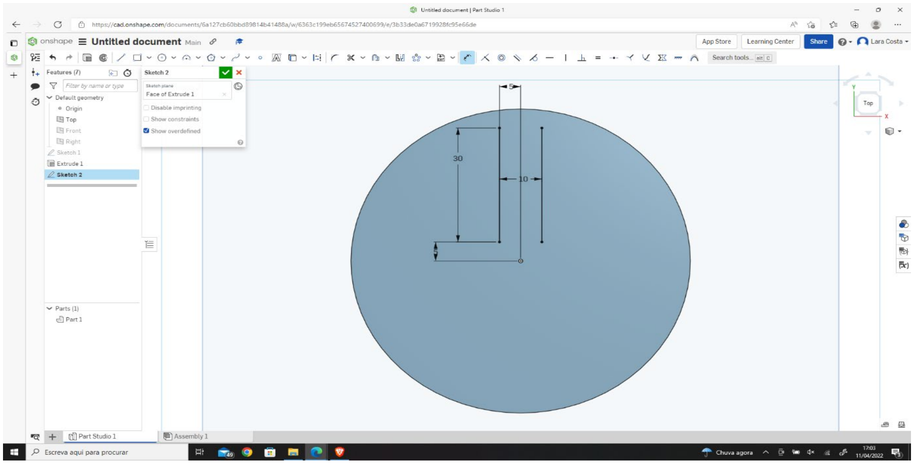
5th Step - Select the top face of the cylinder and click Sketch.



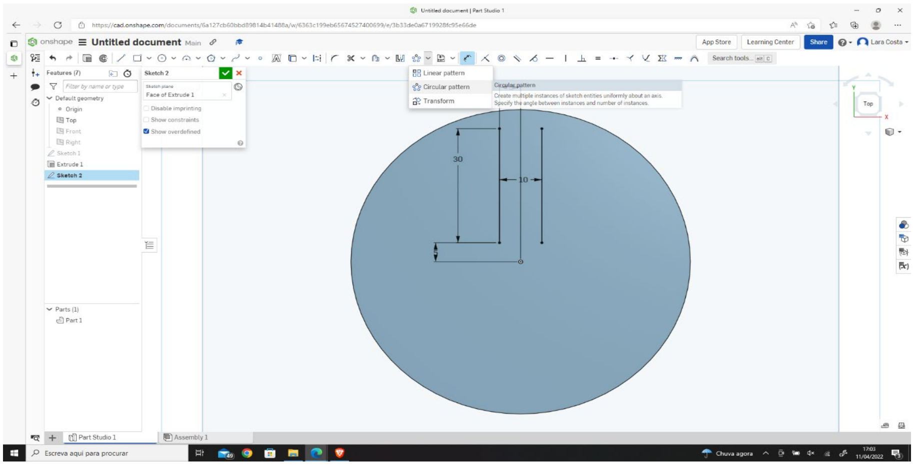
6th Step - Select the sketch tool "line" and draw 2 parallel lines (like in the image).



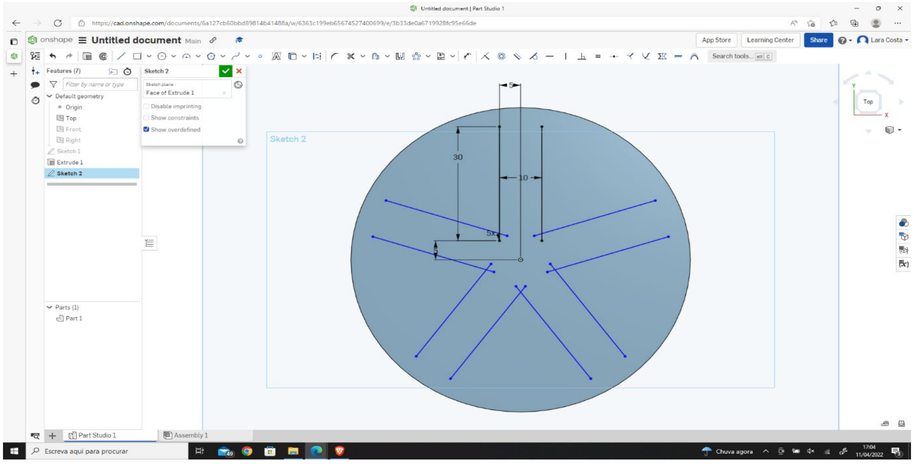
7th Step - Set the dimensions as shown in the image.



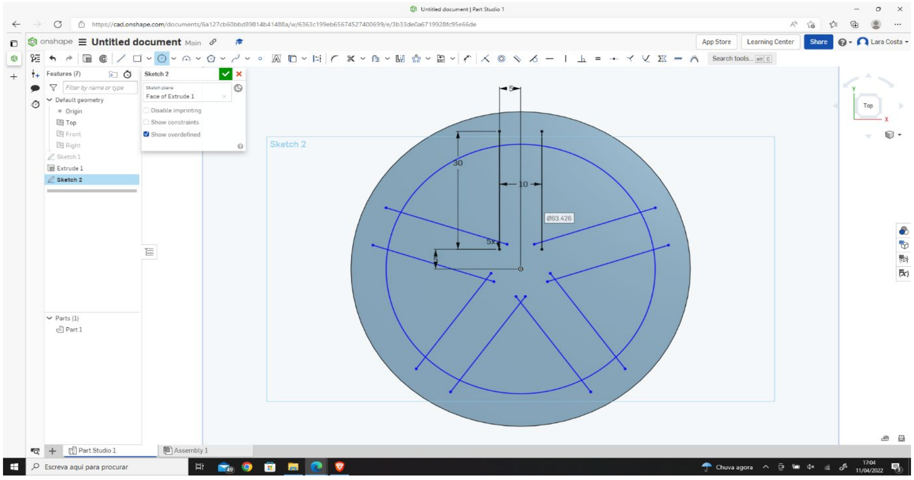
8th Step - Select the "circular pattern" sketch tool.



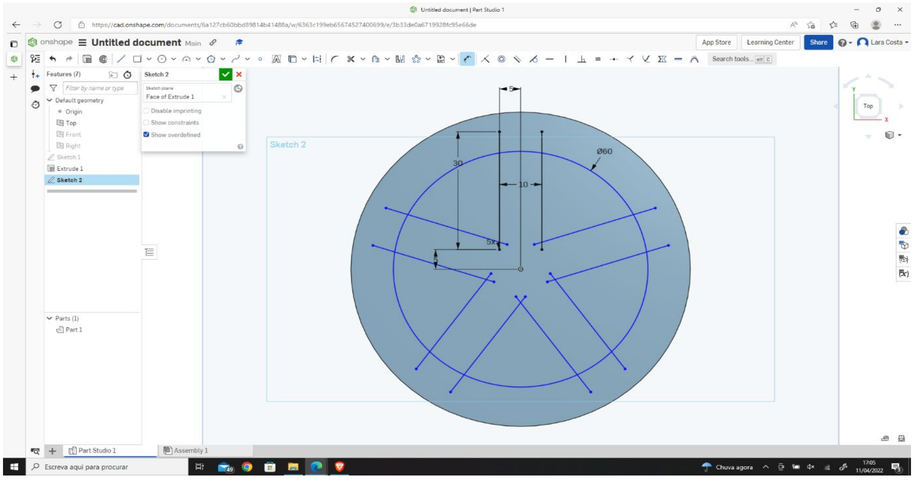
9th Step - Select the 2 lines in orange and change to 5x.



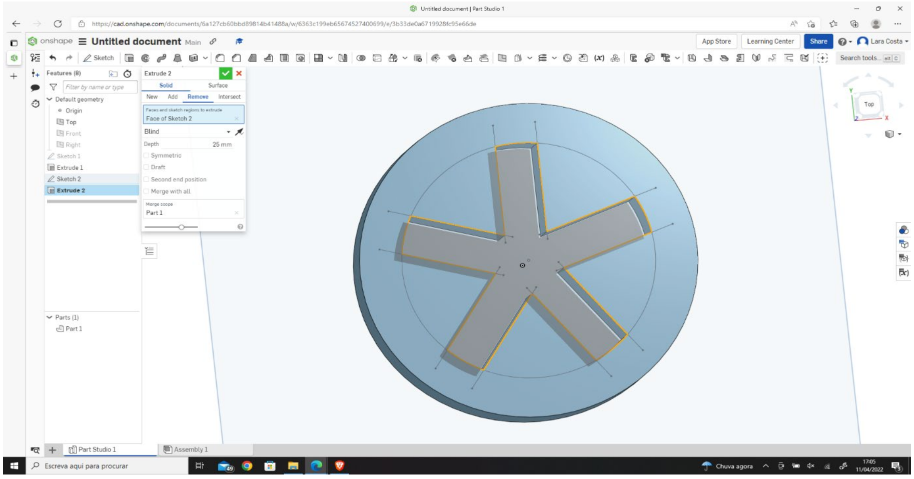
10th Step - Select the sketch tool "center point circle" and draw a circle starting at the centre.



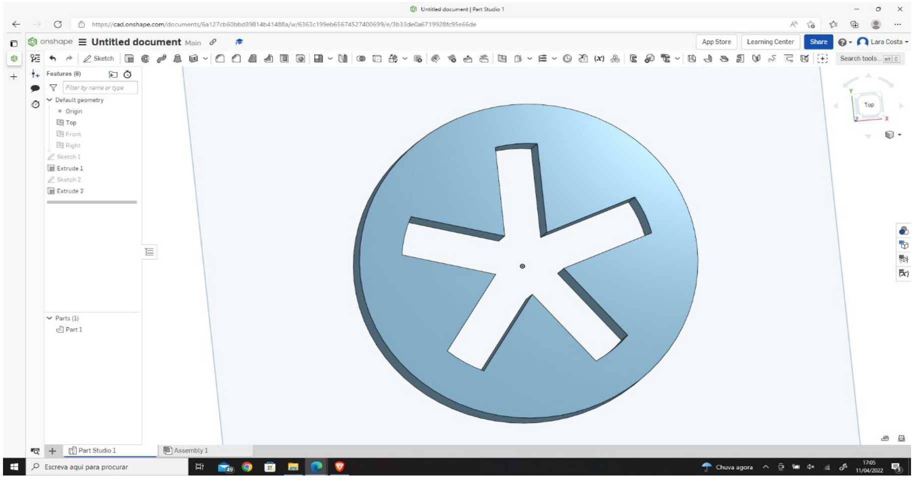
11th Step - Set the dimension to 60mm.



12th Step - Select extrude, then choose to remove and click on the green check mark.



13th Step - The result should look like the following image.



3.6 Introduction to STL

STL is the most popular file type generated by 3D drawing software.

This file is used to transfer the information of our design to the slicing software.

With the slicing software, we will transform the design into information to be printed by a 3D printer.

To do this, we must select the desired part and right-click on the selected parts.

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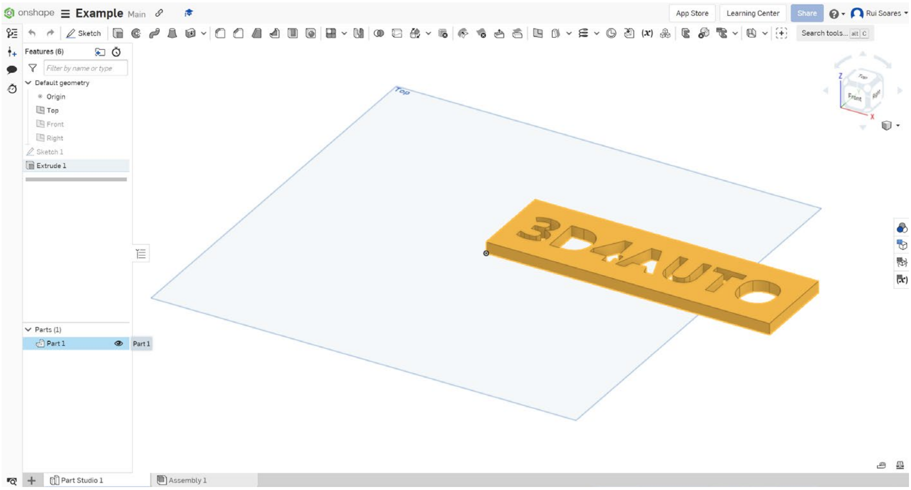
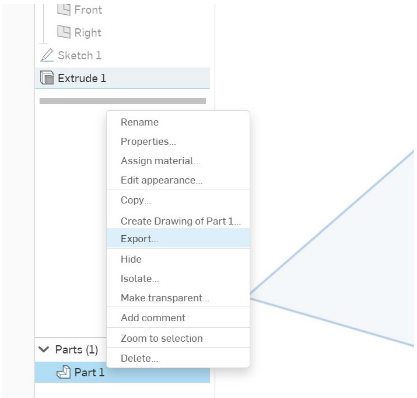
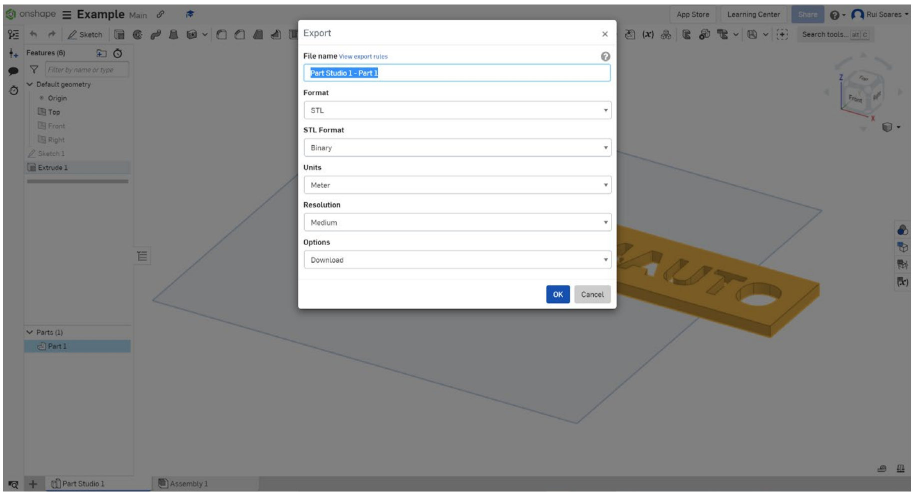


Select “Export”



You can change the name of the exported file and keep all standard settings.



Recommended settings:

Format: *STL*

STL Format: Binary

Units: *Meter*

Resolution: *Medium*

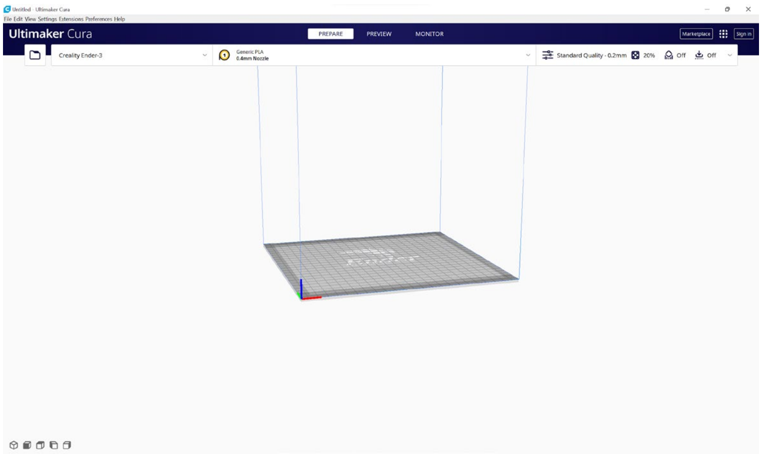
Options: *Download*

3.7 Ultimaker Cura Software

Originally created by David Braam and later bought by the company Ultimaker, Cura is a 3D design slicing software. It is probably the most powerful software on the market, made available in open source for completely free use.

It was distinguished as Tool of the Year 2019 by the Printing Industry Awards in London.

Cura performs the slicing of 3D designs and converts our design, originally in STL, to GCode, a format read by 3D printers. It is currently the most used software in the world by industry, product development departments or home enthusiasts who want to print their own parts.



3.8 Import the STL file to Ultimaker Cura and slice

In 3D printing, it is necessary to have a file with a 3D model (the drawing in 3D format). The most common file is STL.

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Afterwards, it is necessary to convert the file into a special code (G code) that can be read by the 3D printer. This type of encoding is done by slicing software and the process is called slicing.

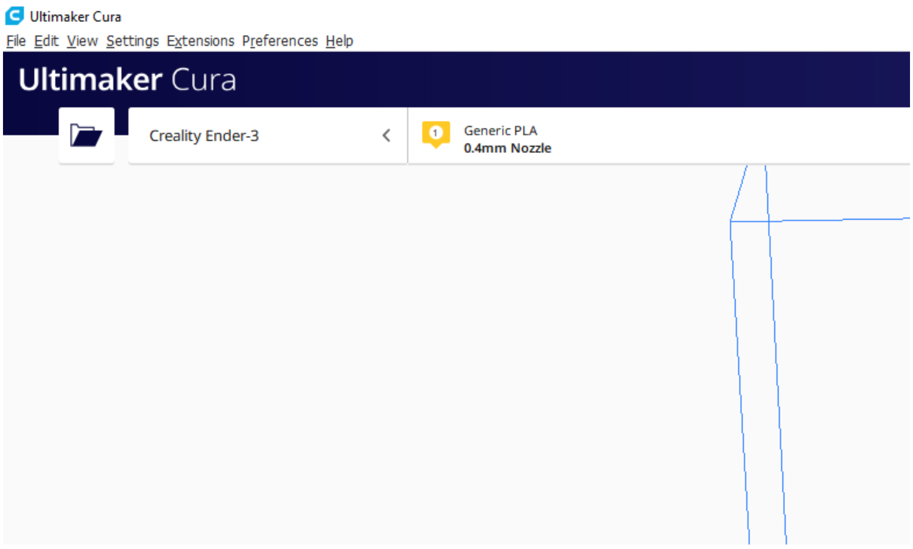
At the end of the slicing process, the user can send the file directly to a 3D printer or save it on an SD card or pen drive, for example. Nowadays, we can also send the file via wi-fi.

The user has many options to choose from as there are several slicing software for 3D printing.

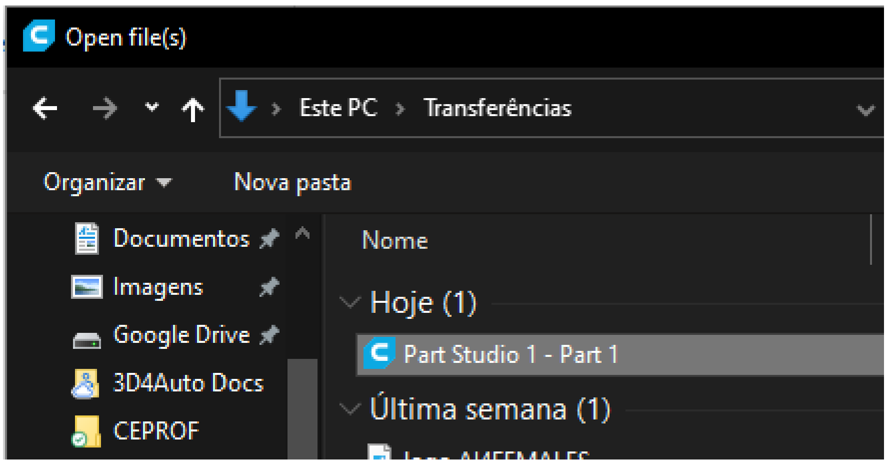
It's for the next part that we need Ultimaker Cura. It's one of the most common and powerful slicing software on the market, and it's free!

So, to convert the design, we must:

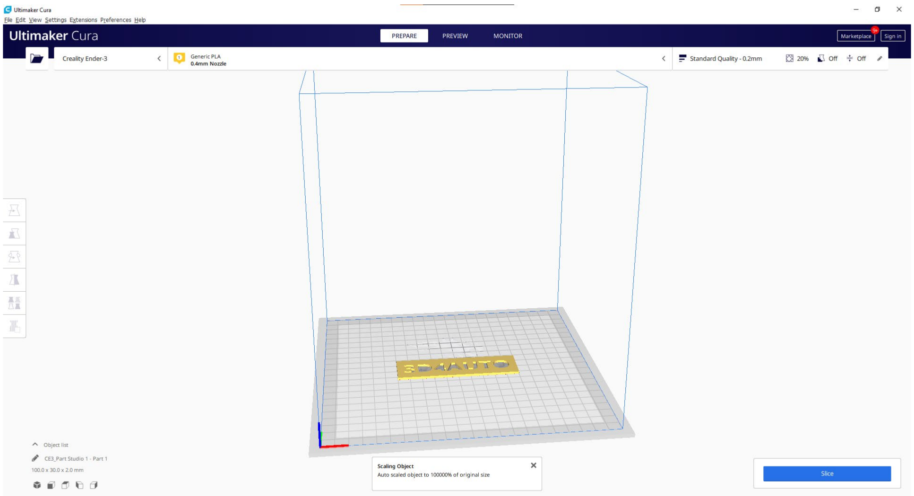
1st Step – Import the STL file to Cura by clicking on the "open" button.



2nd Step – Select your .stl file.

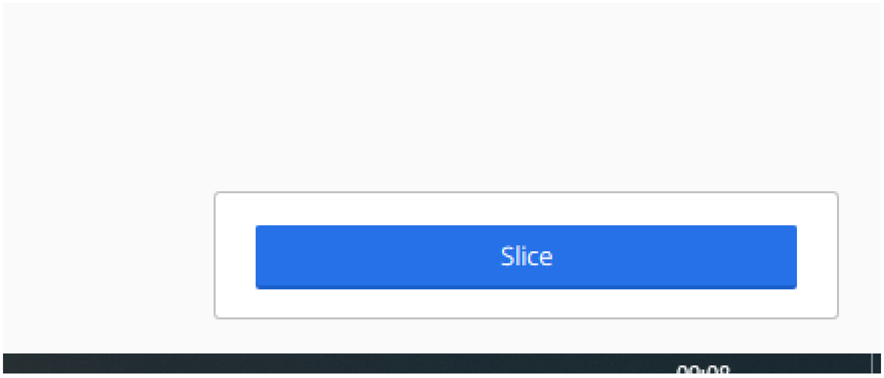


3rd Step – Ensure the part is correctly positioned.

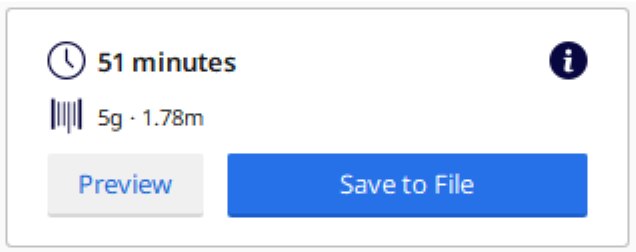


Placing a part/object on a slicer is a process that requires attention because, due to gravity, an object cannot be printed at any given angle. Gravity must always be considered as this type of printing deposits the filament layer by layer and the selected printer operates from the bottom up.

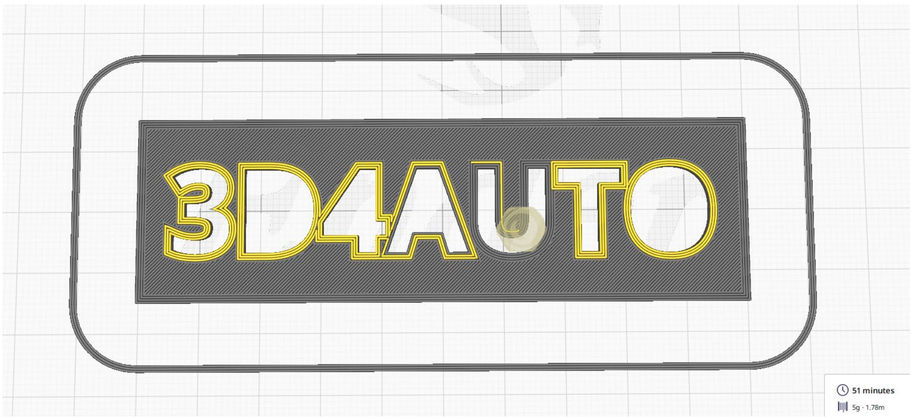
4th Step – Press the "Slice" button.

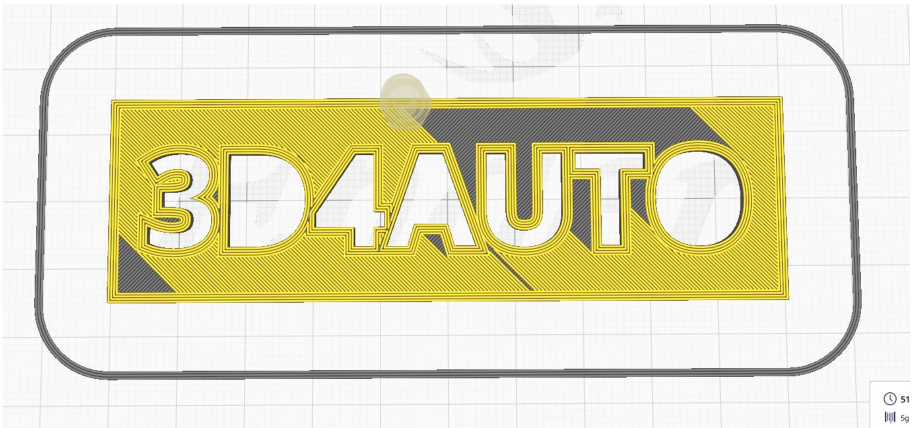


After this, the program will give you some important information like the estimated printing time, and the amount and length of PLA needed.



You can use the “Preview” button to see how the 3D printer will print your part.





You can use the “Save to File” button to download the .gcode file.

The .gcode file contains all the coordinates and lines that the print must follow to print the object. It’s like a GPS route to arrive at some destination but in 3D Printing, the destination will be the completely printed part.

3.9 Conclusion

In summary, in this unit, we have seen how to design a 3D part using the OnShape software, we have seen some of the most important drawing techniques, we got to know what STL and GCode files are and got acquainted with the Ultimaker Cura software.

In this unit, we used the design of a small identifier plate as an example for a project. In the following image, you can find the final result printed in PLA.

4 Slicing Techniques

Rapid prototyping (RP) or Layered manufacturing (LM) or Additive manufacturing (AM) is a process in which a part is produced using layer-by-layer addition of material. The entire production process of prototyping, by RP, is based on creation of geometric model in a solid modeler, tessellation, slicing, generation of laser scanning paths or material deposition paths, layer-by-layer deposition and then post processing operations as shown in Figure 1.

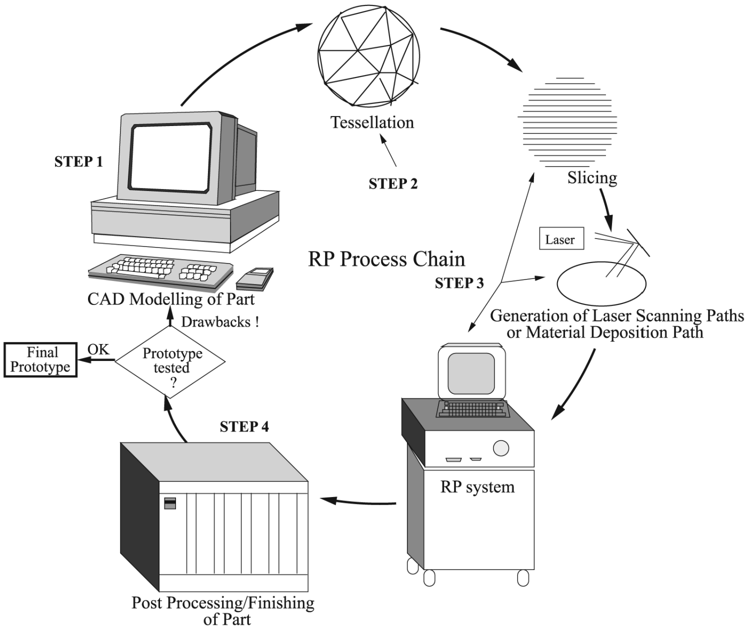


Figure 4-1 - RP process chain.

Tessellation is an approximation process of 3D shape of the CAD model with planar triangular patches. If triangular patches are small tessellated CAD model has dimension and shape closer to original CAD model and vice versa if triangular patches are bigger. Slicing techniques are ways for calculating layer parameters. When talking about slicing techniques we must have in mind that actually talk about algorithms. The algorithms have CAD model data after tessellation as input data and calculate all parameters of each slice. Slicing of tessellated CAD model with a very small slice thickness leads to large build time. On the other hand, if large slice thickness is chosen, the surface finish is very bad due to staircasing. These two contradicting issues namely reduction in build time and better surface quality have been a major concern which has led to the development of number of slicing procedures.

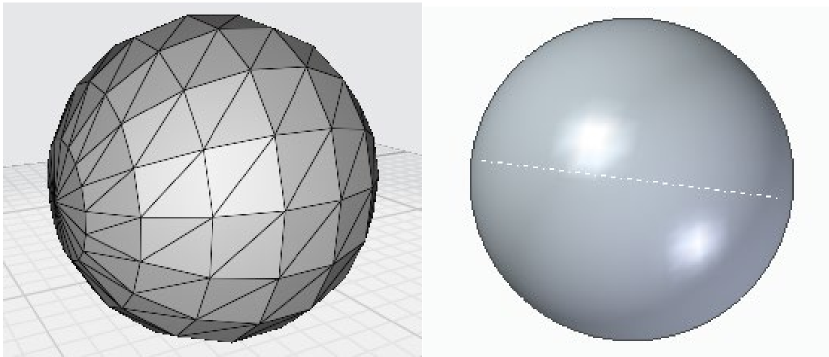


Figure 4-2 - 3D model of sphere and an STL type file of the same model of sphere (tessellation) Triangles-272 Vertices-816.

4.1 Uniform Slicing

The uniform slicing process separates the CAD model into uniform thickness layers from the bottom of the model going upward for printing. Let us accept the CAD model is on the horizontal XY plane of the Cartesian coordinate system fig. 3. Z axis points up perpendicular то XY plane. Let us create a new plane XY_1 parallel to bottom XY plane and above it at distance equal to a layer thickness. Creating a new plane XY_2 parallel to the bottom XY plane and above XY_1 at the same layer thickness from XY_1 there will be two slices of the CAD model. Continue the process with consecutive XY_i planes parallel to the bottom XY plane at uniform thickness layers slices the whole CAD model. To extract the profile of each layer, every line formed by a triangle intersecting the cutting plane is recorded. The process of searching the intersecting triangles can be optimized by sorting the vertices of the triangles in order of the corresponding Z values.

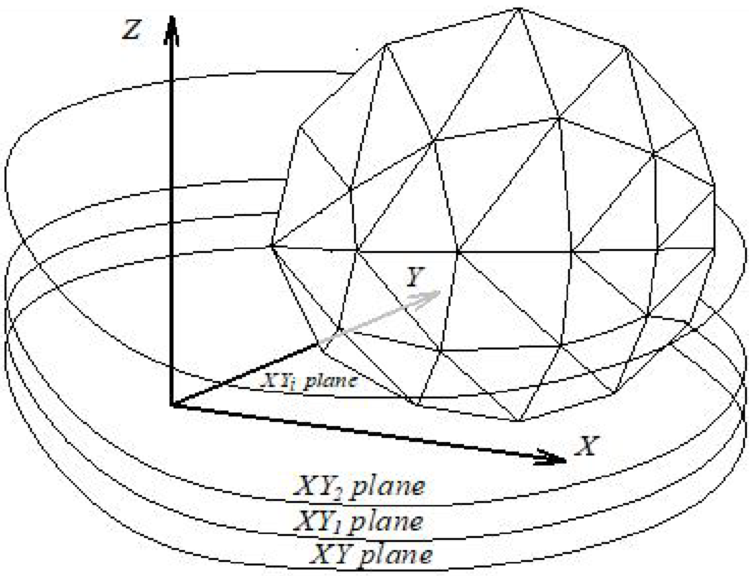


Figure 4-3 - Slicing planes through tessellated CAD model.

Therefore, the lowest Z vertex and the highest Z vertex can be determined for each triangle. The intersections are only calculated on the triangles whose cutting plane is between the lowest Z vertex and the highest Z vertex. Different situations of the intersection of each triangle with the cutting plane are classified as shown in figure 3.

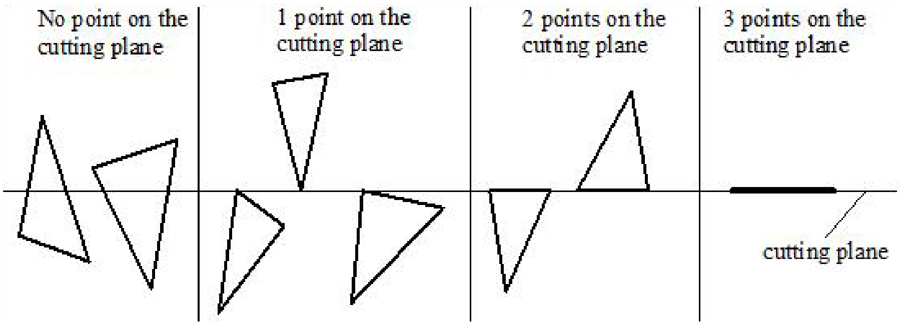


Figure 4-4 - Different slicing conditions.

For each individual triangle facet:

1. No vertex of a triangle lies on the cutting plane. In this case the line between points of intersection of the cutting plane and triangle edges is calculated.
2. A single vertex lies on the cutting plane. There is no intersection of the cutting plane and triangle edges.
3. Two vertices lie on the cutting plane. The edge corresponding to the two vertices is the intersection that contributes to the profile.
4. Three vertices lie on the cutting plane. The whole triangle is on the plane. The edges that are not shared by two triangles contribute the profile.
5. Classical line-place intersection methods can be applied to calculate the intersections for the first case. Figure 5 shows a general scenario of finding the intersection of a cutting plane and triangle edges. Formulae are not discussed here.

As the triangles contained in a STL file can be randomly distributed, checking every triangle with each cutting plane can be computationally inefficient.

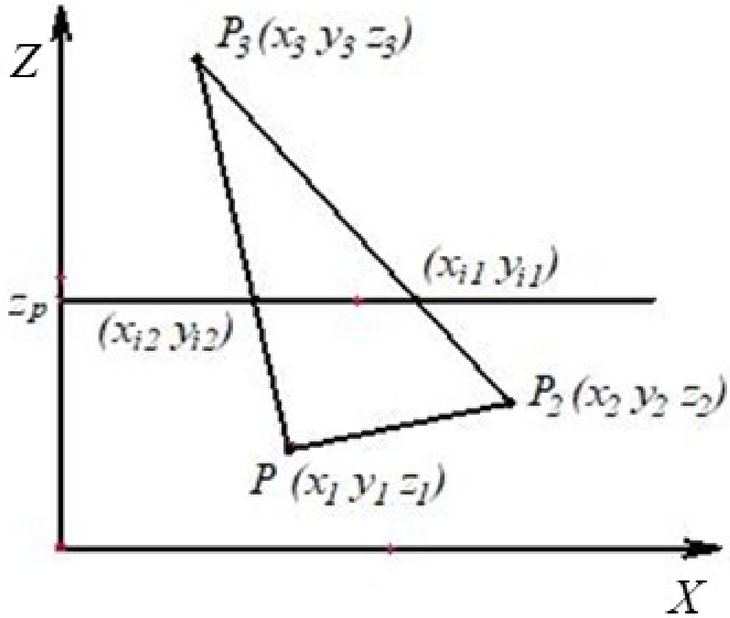


Figure 4-5 - Intersection of a triangle facet.

Therefore, a pre-process can be built for better efficiency. A way to speed up the search for triangles that are cut with the cutting plane is to sort the triangle vertices in the order of z-value. A simple check that can be applied for each cutting plane would be to check the z-values of the vertices of each triangle. If the z-value of the cutting plane is between the minimum and the maximum z-value of the triangle, then that triangle should intersect the plane. The intersection lines can be determined using the method described above. The process is shown in figure 6. Once all intersection line segments have been calculated, they need to be connected to form polygons which represent the contours of the objects. The idea of the algorithm in figure 7 is to find the closest line segment from the current line segment. A tolerance may be introduced to determine if a point is close enough to be considered as a connecting point because the closest points may not have the identical coordinates that determined from the intersection calculation.

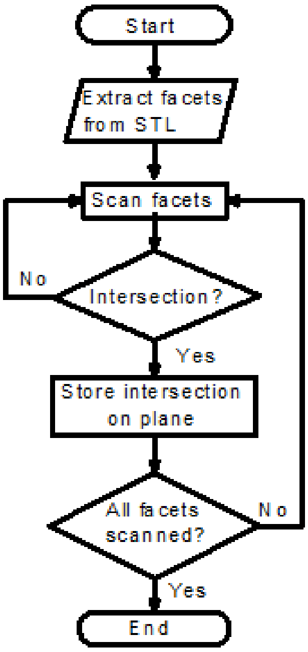


Figure 4-6 - Algorithm for determining intersections from STL data.

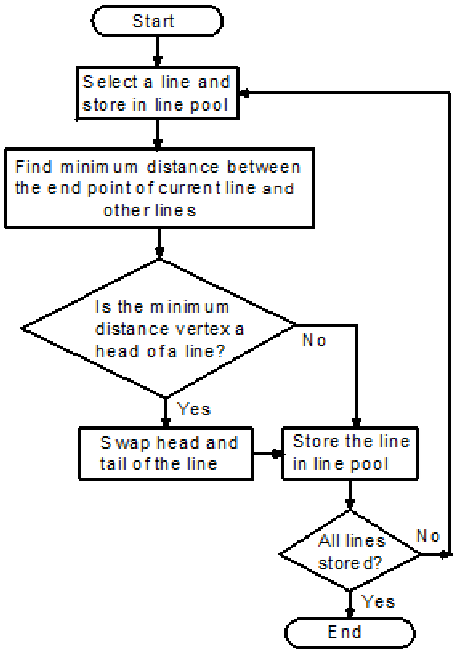


Figure 4-7 - Algorithm for connecting intersections.

4.2 Stair-Step Effect

The stair-step effect is inherent to the uniform slicing process and occurs due to the existence of the stepped edges. There are two types of stairs, outside and inside stepped edges, as shown in Figure 8. In this representation, the contour of the layer edges is considered squared. The presence of the stair-step effect is one of the major concerns for the quality of the prototype. Decreasing the layer thickness could improve the surface finish at the cost of a longer build time.

Stair-step effect have been well studied so far due to many considerations research works and modeling processes. For instance, a model for the stair-step effect in direct metal laser sintering. During evaluation of the model the stair-step effect have been predicted using a numerical approach.

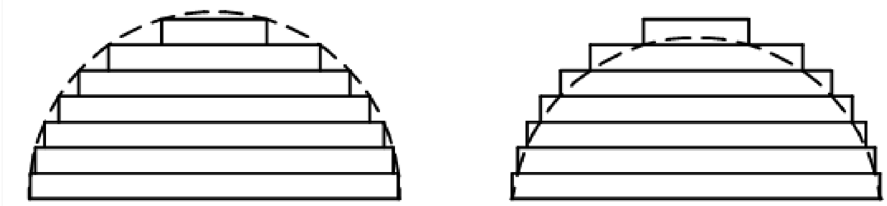


Figure 4-8 - Two types of stepped edges.(a) Inside stepped edge (b) Outside stepped edge

The contour of the layer edges is considered as a circle with diameter of a layer thickness. The surface roughness in additive manufacturing is also examined. The roughness average (R_a) is calculated for 2 different models, that is squared edge and rounded edge. Based on the R_a, the constant layer thickness can be obtained to achieve the required tolerances. There is an attempt to represent surface roughness in FDM (Fused Deposition Modeling) objects. In such consideration, a theoretical model to represent surface roughness distribution under different surface angle is proposed and verified. The cross-section of the deposited filament is considered to be elliptic. The filaments in successive layers are stacking and overlapping. This model is validated by comparing the measured data and predicted data. There is also a development of a numerical model for evaluating the impact of geometric errors on mechanical properties using voxel modeling approach. This research considers the stair step effect as a factor that affects the mechanical property. A voxel-based finite element model is proposed and used in this approach to simulate tensile tests. Another consideration proposed a geometrical description of profile roughness. The roughness average (R_a) in this geometrical model can be numerically calculated from layer thickness and stratification angle.

Some researchers have tried to eliminate the stair step effect by applying secondary finishing operations, which is also known as post processing. There is a proposal to improve surface roughness by CNC milling method. This approach can be time-consuming, as it needs machine setups and operations. Some complex objects can be impossible to machine due to inaccessible features. Another proposal is to use abrasive flow machining (AFM) approach to finish additive manufactured objects. Similarly, an abrasive jet deburring method can be used to finish stereolithography apparatus objects. These approaches attempted to find the best machine setup and process parameters to achieve better surface finish with acceptable machining time. Barrel finishing (BF) method is another approach for improving the surface roughness for FDM objects.

4.3 Adaptive Slicing

To achieve accurate surface geometry without any secondary process, much research has focused on finding optimal layer thickness for each layer to slice a model. The concept of cusp height tolerance was introduced and an attempt was made to restrict the stair-step effect to a user-defined cusp tolerance. Figure 8 demonstrates the idea of adaptive slicing. The layer thickness is determined by a user defined geometrical tolerance. The error between the CAD model and the deposited part is defined in terms of a cusp height tolerance.

As shown in figure 9, the build edges are considered rectangular, and the layer thickness, t, is determined by a pre-defined maximum allowable cusp height. The desired layer thickness can be calculated by

$$t_d = min\left\{L_{max}, \frac{C_{max}}{N_z}\right\} \quad (4.1)$$

where C_{max} is the maximum allowable cusp height, N_z is the z component of the normal vector of the surface, and L_{max} is the maximum layer thickness that the AM machine can produce.

And the slicing layer thickness is given by

$$t = max\{L_{min}, t_d\} \quad (4.2)$$

where L_{min} is the minimum layer thickness available.

The adaptive slicing procedure has been demonstrated by many research applications towards part improvement. It is proposed a stepwise uniform refinement adaptive slicing method. First, the CAD model is sliced with maximum available layer thickness using uniform slicing algorithm. Then, each layer is re-sliced into sub-layers to achieve the required cusp tolerance. An algorithm is introduced named a local adaptive slicing algorithm. This algorithm dynamically slices the model for each local feature. This approach increases the print efficiency significantly by avoiding the slices that do not improve the surface quality. Another algorithm is proposed named a region-based adaptive slicing algorithm. The idea is similar to the previous mentioned one, which treats different regions in the part with different cusp tolerances. This improves the overall efficiency in another way that doesn’t sacrifice the surface quality.

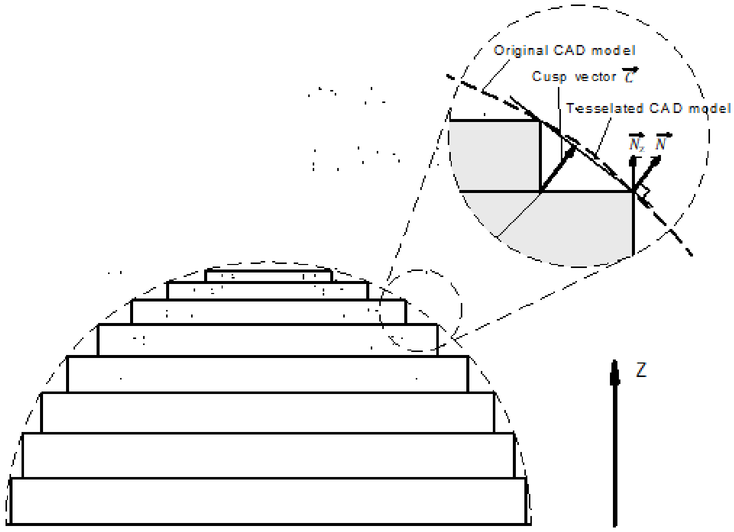


Figure 4-9 - Adaptive slicing and cusp height.

An attempt was made to adaptively slice the model based on the parabolic layer edge profile instead of square. This method calculates the layer thickness in real-time based on the previous layer edge profile and cusp tolerance. An introduction is made of an adaptive direct slicing system based on sloping surfaces criterion. This approach describes the stepped edge profiles using B-spline surface and evaluate the surface error by measuring the distance between the B-spline surface and the cutting vector. There is another proposal for an innovative approach to slice NURBS-based models using adaptive slicing and selective hatching strategy. In this proposal, the peak features are identified and kept during the adaptive slicing procedure. The selective hatching module then computes the hatching area to separate the internal region and the skin region and apply different layer thickness on these two regions. There is developed approach for an adaptive slicing method for multi-axis additive manufacturing models. This approach optimizes the deposition direction to minimize the support structure and builds parts in a 5-axis hybrid system. Adaptive slicing is applied to every deposition direction to maximize the efficiency. Another adaptive slicing method is as follow - instead of the maximum available thickness, this algorithm starts with the minimum available thickness such that any concave or convex corner on the object profile can be represented as accurately as possible after slicing. Then the layer thicknesses are determined based on area deviation and triangle area tolerances of the contour on top and side views. The last method in this summary of adaptive slicing techniques is an adaptive slicing system based on the volumetric tolerance rather than the 2D cusp tolerance. This research categorizes the surface deviation into stair-step effect and surface roughness caused by surface slope and layer thickness. The final layer thicknesses are determined to keep the total volumetric deviation within the desired tolerance.

4.4 Curved Layer Slicing

Other than adaptive slicing procedures, much research has focused on curved layer slicing to address some of the major limitations in flat layer slicing, e. g. stair-step effect and discontinuous toolpath on the top surface. It is proposed a curved layer LOM (Laminated Object Manufacturing) process to manufacture curved layer objects, especially thin curved-shell components. The z value of each point on the curved layer is interpolated from a "height grid". The shape of each new layer is determined by an open-loop method, which offsets a point on the grid with adjacent triangles along with the normal vector of each triangle by the distance of a layer thickness. Then, it fits a surface tangent in the desired four offset triangles with a third-degree polynomial. Another proposal is a toolpath generation algorithm for a curved layer fused deposition modeling (CLFDM) process. The geometry of the filament path is formulated and simulated in this research. There is an integration of adaptive slicing and curved layer slicing based on three-plane intersection method for curved layer offsetting. This method can handle simple shapes to achieve adaptive curved slicing. Some other research has attempted to model and implement the CLFDM for various applications. A discussion has been made for the possibility of applying CLFDM to plastic components with conductive electronic tracks. The CLFDM technology has the potential to build such plastic parts without printed circuit boards and wiring. A proof-of-concept machine was built in this research to validate the hypothesis. An implementation was made of the curved layer fused filament fabrication method on a delta style 3D printer. A parameterized skin surface is manufactured as an example part in this research. The toolpath is generated by calculating the static z value on the surface with known x and y coordinates. The surface finish is significantly improved compared to that of a flat layer sliced part. There is an implementation of a curved-layer additive manufacturing for a large-scale construction process. In this consideration, the toolpath is generated in a plugin of Rhinoceros and converted to G-code. An example is then printed and evaluated using the 3D concrete printing system. The key steps in developing a curved layer slicing algorithm are to collect the vertices and facets on the top surface of the part. After grouping the point cloud of the top surface, the facets and vertices are offset along the normal direction by an amount equal to a layer thickness. As mentioned above, there are different techniques to determine the normal directions depending on the application.

4.5 Direct Slicing

Although the STL format is widely used in industry, there are other ways of defining 3D models and of generating the slice data. In some specific fields, for instance, tissue engineering that fabricate tissue scaffold structures, the final parts are remarkably impacted by the accuracy of the geometrical representation of the CAD model. The bio-mimetic scaffold structures are designed to replace actual body sections, which requires a more accurate representation of CAD models than STL format. Also, for applications that produce large axis-symmetric or spherical geometries, the STL files are usually larger than the CAD file due to its high redundancy in geometry representation. Hence, generating slice data directly from CAD tools by calculate the intersection for a plane with a model would benefit such applications. Many attempts have been done to develop a direct slicing method based on one of the CAD software packages. That CAD software provide slicing packages or support slicing commands in different ways. A direct slicing method was developed based on PowerShape, which is a CAD software for complex part modeling. The models are sliced into layers by writing a macro file, which contains the slicing commands, to the AutoSection, which is a built-in package in PowerShape. Also, a direct slicing method was proposed from AutoCAD solid models. This method sends message written in VBA to AutoCAD to utilize the AutoCAD ActiveX Automation interface, which provides a SLICE command. The sliced planar data are stored in a DXF file. Some research works have tried to develop slicing methods independent of any CAD software. A direct slicing method was developed for STEP based models represented by NURBS surfaces. This method determines the optimal build direction by minimize the build height; refines the NURBS surfaces by adding more control points without changing the original shape to guarantee the convergence occurs within the refined sub-patch; finds the intersection points by bisection iteration routine, then, categorizes the intersection points into entry and exit. This method is independent of CAD software, as it is based on a standard format (STEP) that is supported by most CAD software. There is a proposal for a point based slicing approach. This algorithm first discretely samples the original model and converts it to a point-based representation. Second, the point-based model is sliced into groups of points, which are within a layer thickness in the z direction of the layer height. Then, the layer points are separated into intersection curves, and the boundaries of the curves are fit with B-spline curves. This method bypasses the difficulty of slicing the NURBS model by transforming it to point-cloud model. Prior work has also been explored in the area of adaptive direct slicing. An implementation exists for an adaptive direct slicing method that integrates adaptive slicing with direct slicing. This method reads the DXF file generated from AutoCAD, slices the model into 2D contours using adaptive slicing to guarantee the desired staircase tolerance, then generate tool paths. Another development based on STEP format is an adaptive direct slicing method with non-uniform cusp heights. In this method, different quality requirements can be satisfied for various part surfaces.

The major drawback of direct slicing is that the 3D model representation varies from CAD system to CAD system. Even the most commonly used format, e. g. STEP, is only supported by a few CAD software. Those slicing methods that rely on a specific CAD system cannot be used for other CAD systems.

5 USING TECHNIQUES OF THE 3D PRINTER

5.1 Introduction

Additive manufacturing machines on the market today are developed at a high rate of speed. New processes that are currently in the laboratory stage or under development will break into the market while simultaneously, tried and tested systems will be upgraded within a relatively short time.

All additive manufacturing (hereinafter AM) models are built by joining single layers of equal thickness. The layer is shaped (contoured) in an x-y plane two-dimensionally. The third-dimension results from single layers being stacked up on top of each other, but not as a continuous z coordinate. In the strictest sense, additive manufacturing processes are therefore $2½D$ processes.

The models are therefore three-dimensional forms that are very exact on the building plane (x-y direction) and owing to the described procedure are then stepped in the z direction, whereby the smaller the z step is, the more the model looks like the original. Figure 4-1 shows an example of a three-dimensional model of a plastic and the resulting shift model, which is marked by the stair-step effect.

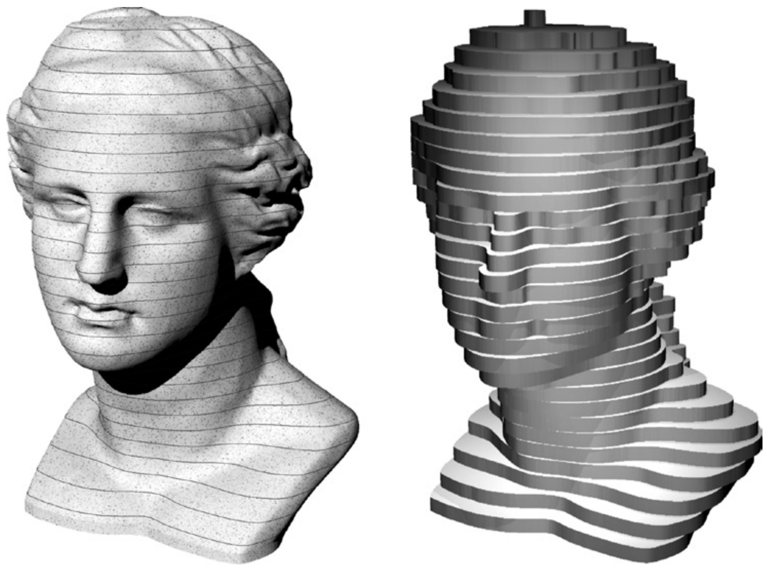


Figure 5-1 - Stepped surface as a result of the layering process. Three-dimensional solid model (left) with marked equidistant layers and the created layer model (right) (Source: FH-Aachen)

The stair-step effect is a typical characteristic of the additive manufacturing process that can never be entirely eliminated but can be reduced by decreasing the layer thickness [1].

5.2 Print technologies: liquid-based print

In the field of additive manufacturing technology, currently non- or low-crosslinked monomers of the type acrylate, epoxy, or vinyl are used as liquid original materials in ambient conditions. They are locally cross-linked by ultraviolet radiation to form solid layers and components. The processes are called photopolymerization, stereolithography, or stereography.

5.2.1 Photopolymerization - Stereolithography (SL)

All processes in which the underlying mechanism is the solidification of liquids are based on the concept of (photo)-polymerization. They use a viscous monomer with few or no cross-links that is interspersed with suitable photoinhibitors. Exposure to ultraviolet radiation sets off a spontaneous polymerization, in the course of which the liquid monomer becomes a solid polymer. This process, which in principle also works with all UV light sources and under sunlight, is adjusted to the special requirements of additive manufacturing processes regarding exposure strategy.

The laser scanning process is the oldest and still the most accurate process. A fine laser beam forms the contour of the respective cross section on the surface of a resin bath and generates locally the critical energy density that is required for the polymerization and thus the desired solidification. In current industrial methods, a single laser beam provides the required energy in the focus. Especially in microtechnology, the two-photon process is applied.

There are two methods in the mask process. The entire cross section is imaged onto a transparent mask in the lamp-mask process and is projected by means of strong UV lamps through this mask onto the surface of the resin bath. In the projections process, a powerful projector (beamer) performs both functions and projects the information layer directly on the surface to be exposed.

In the nozzle-lamp process, the component is produced by means of a nozzle and then polymerized by means of a UV lamp.

5.3 Polymerization: Stereolithography (SL) devices

Local polymerization as a principle of selective hardening of liquid or paste monomeric precursors occurred in the first 10 years after the launch of additive processes exclusively as laser stereolithography (more precisely, but usually not referred to as, laser scanner stereolithography). Meanwhile, processes have gained importance that work with masks (lamp mask method) or with print heads (polymer printing process). The methods coexist, and each requires customized processes and machines.

The stereolithography commercialized in 1987 is still the benchmark for many other additive processes. More important at this point, the detailed description of the production that is suitable for stereolithography parts gives a sense of additive processes as a whole and can be transferred to other methods in many aspects.

5.3.1 Machine-Specific Basis

The industrial application of the principle of solidification of liquid or pasty monomers by polymerization is called stereolithography. It includes laser scanner stereolithography, lamp mask stereolithography, the polymer printing method, and the polymerization of pastes. Variants for contouring and solidification of the layers will be presented in subsections.

5.3.1.1 Laser Stereolithography

The company 3D Systems name their stereolithography method Stereolithography, SLA; the company EOS called it Stereography. The terms are trademarks or registered names of their respective companies. Laser scanner stereolithography is the ancestor of all industrially offered additive manufacturing processes and is represented with 4500 installed systems worldwide (as of the end of 2006); after the extrusion machines, it has the most industrial applications. The following section focuses on laser stereolithography but shows parallels to related processes where this seems appropriate.

5.3.1.1.1 Principle of Layer Generation

Laser stereolithography is based on the point-wise solidification of photosensitive monomers (polymerization) using a laser scanning exposure apparatus (galvo scanner).

Stereolithography machines utilizing the laser-scanner method consist of a container of liquid monomer, the installation space, which is usually also used as a reservoir, a construction platform, which is displaceable in the z direction in this container, and a laser-scanner unit, which writes the current layer information on the surface of the resin bath. The platform supports the part by support structures. This allows for the production of overhangs, fixes unconnected parts of the model, and ensures the defined building up and subsequent removal of the construction platform. After solidification of a layer, the construction platform is lowered by one layer thickness. Thereafter, a new layer is applied (recoating), and this layer is exposed to the data of the new layer and thus solidified. Then, the process proceeds to the exposure of the following layers. In this way, the part “grows” in layers from bottom to top (Figure 4-2).

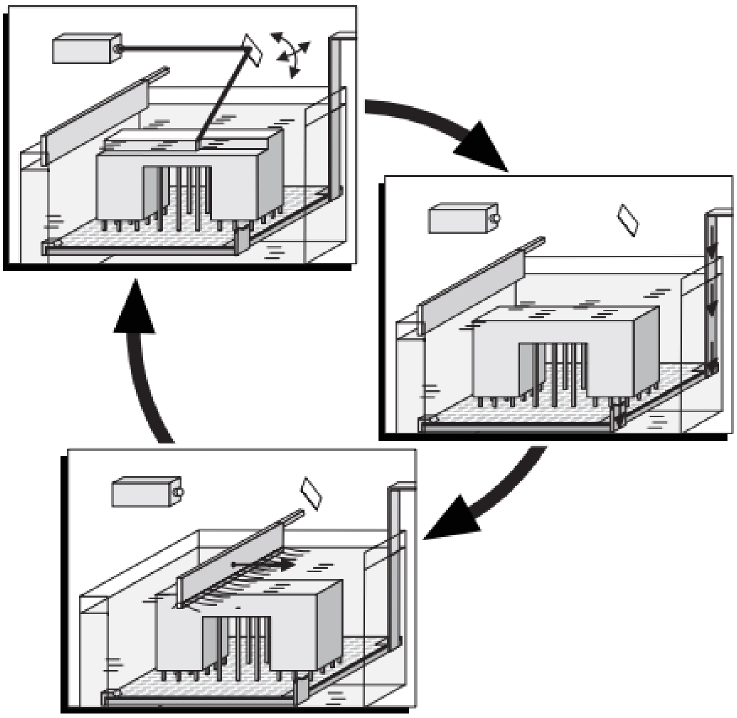


Figure 5-2 - Stereolithography (laser scanner) principle

Stereolithography processes try to realize the solidification of a layer with a row of single consolidations, so-called voxels. The geometry of the voxels is given by the energy distribution in the laser beam and the penetration characteristics of the resin. The ideal geometry has the shape of a paraboloid of revolution. In order to achieve the necessary component strength, the laser penetrates both of the voxels in one layer and the two adjacent layers ("overcure") so that the actual penetration depth of the laser is greater than the layer thickness (see Figure 4-3). The generation of a layer and the toothing with the underlying previous layer takes place simultaneously.

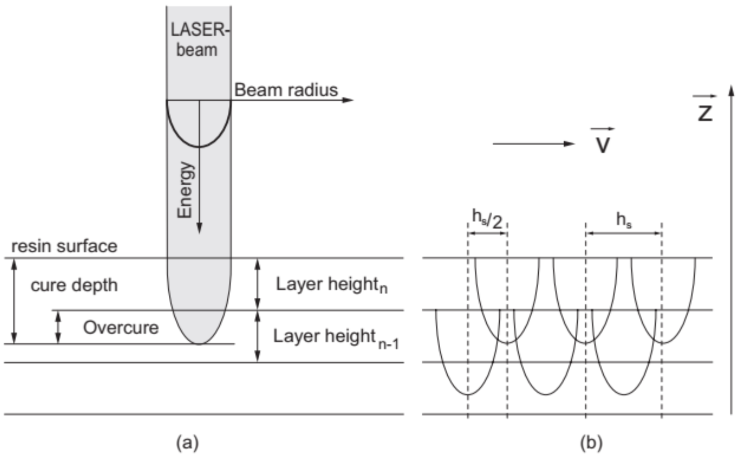


Figure 5-3 - Exposure to the laser beam on the resin surface: (a) conditions in the single beam; (b) voxel structure

In practice, the tuning of laser power, beam parameters, scan speed, and material parameters (resin type) determine whether a voxel structure actually arises in the layer or whether virtually continuous paths are written.

For fast and accurate polymerization, each manufacturer uses different exposure strategies. Basically, the areas to be solidified are contoured by boundary curves (borders) and finally hardened inside by appropriate hatching (hatches). For exact generation of the boundary curves, the beam diameter is compensated. For this purpose, the path of the laser is postponed by half of the amount of the beam diameter of the geometrically exact contour into the component (beamwidth compensation or line-width compensation). In addition, the beam diameter is changed in some systems.

As a result of polymerization, the volume of the liquid resin decreases, and the component shrinks. The problem of shrinkage has been substantially mitigated with the change of acrylates to epoxy resins in the second half of the 1990s (linear shrinkage: acrylate = 0.6 % versus epoxy resin = 0.06 %). However, epoxy resins require up to three times higher exposure energy. Methods that use lamps for the polymerization therefore operate today preferably with acrylates. To counteract the effects of shrinkage, there are a number of building strategies that can be used in addition to the optimization of the process parameters. One way is to not continuously connect opposite walls but periodically generate spaces that counteract the deformation due to internal stresses (retracted, 3D Systems).

Components produced by the laser scanning process have a relatively low strength (green strength) during the construction process. They can therefore be easily deformed by the coating mechanism, internal stresses, or by their own weight. For this reason, protruding elements or cantilevered walls must be lined at a certain overhang or slope angle by supporting structures (Figure 4-4).

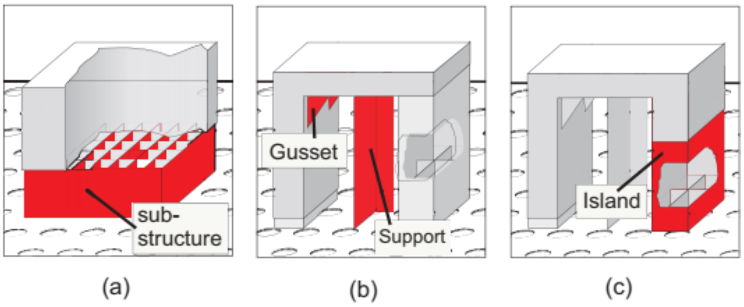


Figure 5-4 - Support structures: (a) base; (b) support; (c) "island"

In addition to this function, supports also serve to pull down device areas that want to "roll up" due to shrinkage processes (curl) and to position and fix the component on the build platform. Until the past few years, supports were considered as volume elements and formed a wall like a square of twelve triangles. They also had special features. The supports in Figure 4-4(b) are designed as elbow fittings (gussets) to support the particular rectangular geometry branches. Figure 4-4(c) shows a structure that is also called an island. It is used to position and support the component areas that start at later layers and later grow together with the rest of the component. The handles of cups, for example, could not be manufactured without support because otherwise they would start "in the air."

With such support structures, the amount of data grows considerably, especially in STL formulations. Therefore, the triangles (seen from above) were generated only in one line and thus produced without any volume in CAD. But the track gets a volume in the SL process due to the width of the laser tracking. Figure 4-5(a) illustrates this situation. The color of the triangles shows the alternating direction of the normal vectors. Figure 4-5(b) shows the conditions on a real device. Shown are supports that were built with the Fine Point Method (3D Systems). Due to their small diameter, a particularly fine connection can be removed easily and almost without damage to the part.

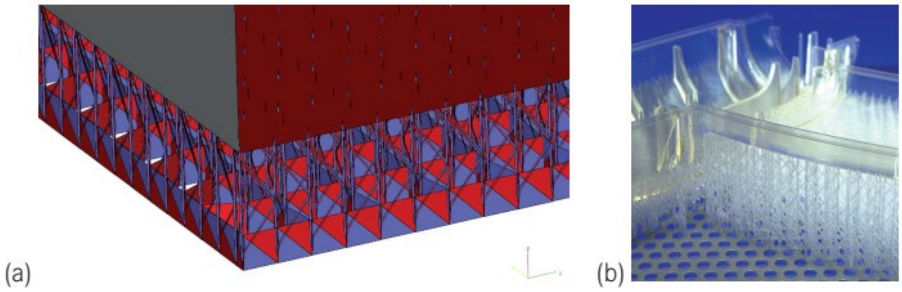


Figure 5-5 - Supports: (a) support as a volume element; (b) situation in a real part

Supports are generated (automatically) during the data preparation, but they must be manually removed from the finished part. In some methods, for example FDM or PolyJet, the supports may also be washed out automatically.

Regarding hollow-built stereolithography components, all manufacturers implemented building strategies for the stereolithography processes with a larger cavity volume fraction because of the increasing speed of construction and material savings, but especially to use the models directly as lost forms in the investment casting process (burning of ceramic porcelain molds). In fact, solid walls are designed as spatial trusses, that is, as two thin partition walls, which are interconnected by webs. In addition, so-called outer layers (skins) must be introduced to complete the model or individual model parts up and down (in the z direction).

Hollow-built stereolithography components must have openings through which the noncross-linked monomer may leak. These openings must be closed if the model is going to be used in investment casting so that the ceramic mass does not run into the model; in this way casting defects are avoided.

With the consolidation of the last (top) layer, the building process is complete. The device, which is now fully immersed in the monomer, is moved out of the resin bath upward so that the excess resin can drain and drip back into the resin tank. In terms of economic utilization of the machine, it is advantageous to provide for the component to drip into a separate, preferably heated drain container. Committed users have constructed devices for themselves that support the bleeding of the resin by the spin of a honeycomb related centrifuge process. This is particularly of advantage for hollow-built walls.

5.3.2 Advantages of Stereolithography

Stereolithography, also known as stereography, is presently one of the most accurate of all additive manufacturing processes. Its accuracy is limited by the machine, but not by physical limits. For example, the minimal depictable land widths are in principle a function of the laser beam diameter. The fineness of the *z* stepping is not limited by the process. It is limited by the wettability of a solid layer by the (following) liquid monomer layer, expressed as the relationship of the volume power (proportional to the layer thickness) and the surface tension. Thin layers consequently tend to "rip." There are more cost-related reasons that are decisive in practice; for example, thin layers extend the construction period and therefore increase cost.

It is in principle possible to contour the boundary of the *x*-*y* planes in the *z* direction by appropriate control (five-axis) and exposure strategies (variation of pulsepause relationship and laser performance) and thus to achieve a quasi-continual *z* modeling.

Stereolithography not only allows the production of internal hollow spaces, as do nearly all of the other AM processes, but it also permits their complete evacuation as a result of the process technology. For this, a drainage opening is necessary that should obviously be much smaller than the diameter of the hollow space.

Stereolithography materials were formerly all transparent or translucent, and therefore they allowed the visual assessment of internal hollow spaces. This is useful, for example, in many flow studies and medical applications. Today most of the materials are opaque and nearly white like Somos 14120 (DSM), Accura SI 25 (Systems), and RenShape SL7580.

In processes with a resin bath, only individual regions of the component are provided with supports. In general, the volume of the support is significantly less than that of the component and may be affected by the operator. The entire volume of the component will always be solidifying in polymer printing processes and film transfer imaging processes (FTI) and consist of either the construction material or the supporting material. The volume of the support structures is therefore quite high. The support material is waste.

Noncross-linked monomers can be reused, and completely polymerized resin can be treated as household garbage. But liquid monomer is hazardous waste.

Complex models, or those of larger dimensions than the construction chamber, can be assembled from single partial models into arbitrary, complex, complete models. If the same photosensitive resin is used as binder and UV radiation sources are used for local curing, the section points are unnoticeable in respect to their mechanical-technological properties, and they are also invisible to the eye.

The models can be finished by sand blasting and polishing and, to a certain extent, by machining and coating.

5.3.3 Disadvantages of Stereolithography

Owing to its process technology, stereolithography is restricted to photosensitive material. In resin development the focus is on cross-linkability with UV radiation. The usual primary properties such as resistance to extension, elasticity, temperature stability, and so forth are of secondary importance. Furthermore, material development is limited to stereolithographic usage because the apportionable costs of the product offset this. Stereolithography is a two-step process in which the models are first solidified to a high percentage (> 95 %) in the actual stereolithography machine; afterwards the green product must be cleaned with solvents (TPM - tripropylene glycol monomethyl ether - isopropanol) and it is placed into a postcuring oven to build up further cross-linkages with the help of UV light until it is cured completely. Printer and mask processes are single-stage processes. They polymerize the component completely and therefore work without cross-linking after the process. When making stereolithography models, unsupported structures and certain critical angles of overlapping model parts cannot be realized without support. Therefore, supports are needed. These support structures shall be placed in the context of model preparation using appropriate programs. The component and the supports of laser-based processes consist of the same material. The supports have to be removed manually from the green product or from the cured model. In the printer or mask processes, the supports are usually made of a thermoplastic hard wax that is washed out after the building process. It can also be removed automatically or semimanually with the help of solvents. Because all areas of the building volume that do not belong to the component are filled with supporting material, a separate supporting structure is not necessary. In addition to the construction process, the application of stereolithography limits the removal of the supports, and depending on the process, the storage, handling, and disposal of solvents are necessary. To a small extent, photosensitive acrylates absorb oxygen, whereas epoxy resins are hygroscopic; this has to be taken into account when storing and processing the material. The models tend to creep even after being completely cured. After a few days or weeks, unsupported walls show sagging that disappears if the model is turned over or supported. The newest epoxy resins show these characteristics less prominently.

5.4 Print technologies: powder-based print

5.4.1 Melting and Solidification of Powders and Granules: Laser Sintering (LS)

Powders or granules in a powder bed are the materials used for the formation of a defined solid layer. They are partially melted or melted in the respective layer level by an energy source and solidified after cooling into a solid body. Energy sources can be energetic single beams such as laser beams, electron beams, or an infrared panel heater.

The processes are called sintering processes in reference to the nonadditive manufacturing diffusion-controlled sintering process. For many years, laser-based processes were exclusively commercialized and were called laser sintering (LS) or selective laser sintering (SLS). It is called even-beam melting or simply melting as a generic term because today electron and infrared rays are also used.

In the classical nonadditive manufacturing sintering, two neighboring particles are joined by a substance exchange. For this, high temperature and high pressure over a relatively long period of time are needed. The sintering process is dominated by the mechanism of surface diffusion. It begins in the form of a neck at the contact point of the particles. With progressive sintering, a material transport takes place—preferably along the grain boundaries—and continues in the inside of the particles (grain boundaries, volume, and lattice diffusion). The sintering that is used in additive manufacturing does not require the two essential components of the classical sintering process: high pressure and long time. It must therefore be assumed that the additive manufacturing sintering does not occur or is not diffusion-controlled. Only a short thermal activation of the nonadjacent particles in the powder bed takes place. When these are melted on the surface after cooling, it results in a more or less porous component. When the particles are completely melted, a dense component is formed.

The result is usually slightly porous components. For plastics, this is often for process reasons intended to avoid warpage and internal stresses. But metal parts are dense. Therefore, most of the processes with metal powder melt the powder completely. It is also called laser or, more generally, beam melting.

The sintering process will be described essentially by the interaction between the viscosity of the melted particle areas and their surface tension. Both of these (opposite) effects are dependent on the temperature and the material. Some details are therefore considered in the following sections in the context of the materials.

Fundamental studies on the mechanisms of selective laser sintering, which also address the interaction with the practical application, originate from Alscher [9] and Nöken [10]. Ader [11] has revised the theory with a focus on ceramics.

5.4.2 Principle of Layer Generation

In the laser sintering process particles of usually 50 to 100 μm, which are closely packed together to form a powder bed, are slightly pressed if this is necessary for the process. They are then slightly melted locally by a laser beam, solidified by cooling due to heat conduction, and are thereby joined together to form a firm layer (see Figure 4-6). The unmelted particles stay in the part as support material and are removed after the end of the process. By lowering this layer and recoating it with powder is analogous to the first layer, the second layer is solidified and connected with the first. Figure 4-6 shows the principle of the process on the basis of laser sintering.

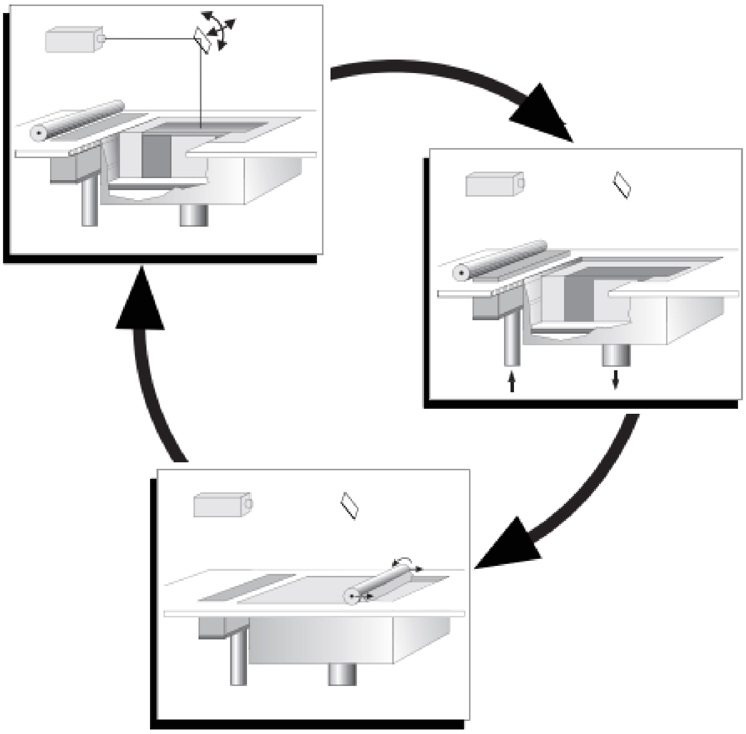


Figure 5-6 - Principle of laser sintering and melting

5.4.2.1 DESIGN

The process chamber offers the building room, which can be enhanced by lowering the bottom of the chamber by one layer height. It is important for the technical functioning of this process to construct the process chamber in such a way that it can be preheated up to very nearly the melting temperature of the sinter material. This is the requirement for the quasi-isothermic sintering of plastics. The energy source (laser or electron beam, infrared lamp) therefore only needs to add a small differential energy for the sintering. The process temperature must be kept as steady as possible and within narrow tolerances (a few degrees). Furthermore, oxidation of the material must be avoided, which is usually achieved by inerting the machine. This is done by generating a nitrogen atmosphere inside the machine (0.1 % to 3.5 % residual oxygen, depending on the material).

The laser sintering process always works without supports because the unsintered powder stays in the bed and supports the model. Depending on the geometry of the model and the material being used, it has proved to be useful to build a platform (base) as well and to build on this base. Metal processes reduce tension by the use of support structures. In addition, or alternatively, firm understructures can be constructed if required using specialized construction strategies. Starting with about half laser performance and double scanning speed, and by adjusting the laser performance as well as the scanning speed to the optimal parameters within several layers, structures with low distortion are generated that favor a reliable model construction.

To maintain an even temperature field, it is useful in some cases to place loose parts deliberately near the model or to put a grid around the component. Metal processes work with support structures to position the parts at the platform and to avoid deformation.

Some users suggest positioning the model, especially long drawn-out parts, under the so-called Kodak angle relative to the cylinder's longitudinal axis. It is assumed that especially distortion-free components can be generated under this angle. Some sources mention an angle of about 15°, others about 10°.

In practice, nearly all models are positioned in the machine without a base according to the criteria of accuracy and economy. When the build parameters are carefully matched, and especially when the temperature fields are kept even, the results are excellent.

To achieve models without defects, it is necessary to adjust and control the temperature and the temperature distribution in the build chamber very carefully. Temperature differences of a few degrees can cause useless components that are either poorly sintered or deflect due to excessive heat and even change color, depending on the material. Therefore, temperature control plays an important role. Current machines have very precise temperature control.

5.4.2.2 Postprocessing

For plastics, after the construction process, the compound is completely enclosed in a powder cake. Most sintering processes take place at a temperature of between 170 and 200 °C, especially when plastic materials are sintered. To ensure a uniform cooling, it is important that after the last layer an additional layer of powder several centimeters thick is applied. After the compound has cooled completely, which may take several hours owing to the poor heat conduction, the powder cake is carefully removed from the exterior (Figure 4-7). If changeable build chamber modules are used, the removal and cleaning process takes place half-automatically in screens and with high pressure outside the machine. Although, in theory, the compound is merely embedded in a loose powder cake and only needs to be taken out and the powder blown off, in practice it is wise to proceed carefully. First, the compound can be easily damaged because its position is not exactly known; second, there are, depending on the temperature control, slightly sintered areas around the model (fleeces) that have to be removed with great care by using special tools. Therefore, patience and skill are required in cleaning sintering models, especially those with internal hollow spaces, drillings, and fine details. To exacerbate the situation, the models and powder have the same color.

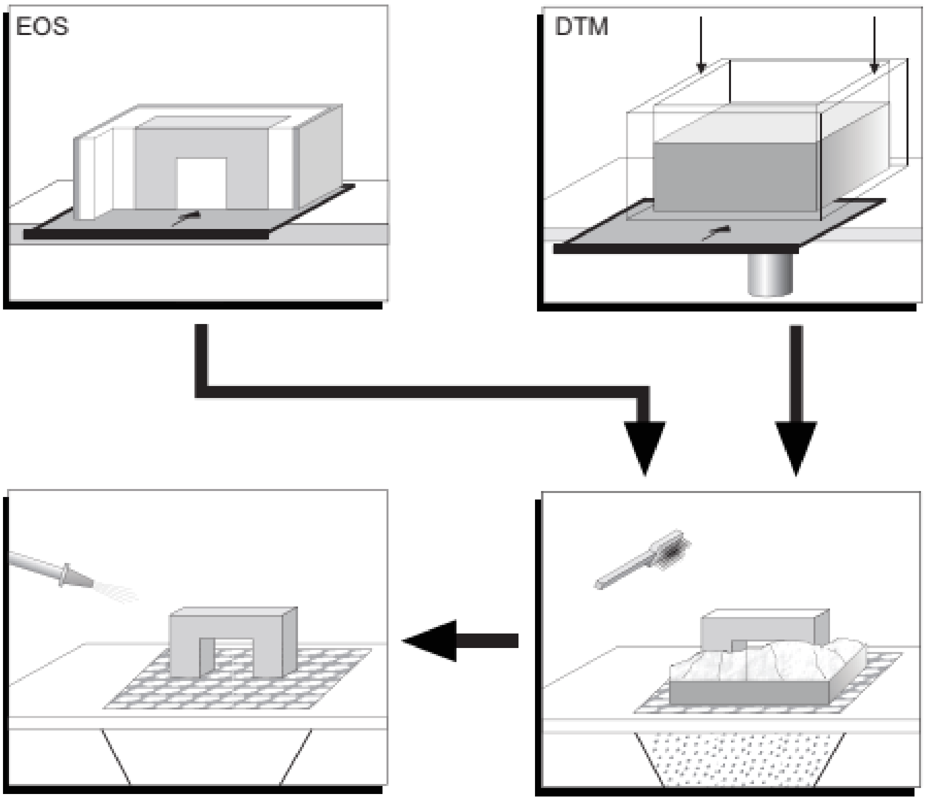


Figure 5-7 - Laser sintering, postprocessing principle

For metal processes, the postprocessing is easier because the process chamber and the powder stay nearly cold. The problem is that they use support structures, which have to be removed. Direct ceramic sintering machines work with high preheating temperatures.

After the parts are cleaned in the postprocessing, the surface is treated further by manual polishing or sand blasting. Parts of models or broken-off parts of models can be glued on with cyanoacrylate glues or with epoxy resins. To finish the models, cylinders filled with polishing material can also be used. It has to be taken into account that the type of the abrasive used determines the amount of material removed. There is a high risk of rounding sharp-edged corners. Because sintered models are generally porous, all infiltrating surface sealings could generally be used. This includes all kinds of hard wax, epoxy resins, and also primers on an enamel base.

Every kind of postprocessing changes the geometry. This is important because the additive manufacturing processes produce parts directly from the 3D data sets.

5.4.2.3 Follow-up Processes

Laser sintering processes are preferably used for functional prototypes (functional parts) or for direct production (rapid manufacturing). Therefore, the direct application is used more often than casting processes. Vacuum casting is possible in general but requires that the surfaces be exceedingly well finished.

Metal parts could be achieved either by direct selective laser melting (SLM) or by precision casting on the basis of additive manufactured master models. It is especially interesting to use polystyrene or polycarbonate models directly for precision casting. This procedure is successful only if an appropriately careful wax impregnation and surface preparation are applied. The model itself must be preheated up to approximately the temperature of liquid wax (between 190 and 210 °C). The impregnation can take up to 30 min; if critical spots have to be reworked manually, it could take significantly longer. Finally, the classic precision casting process is started. The thorough baking should be done with sufficient oxygen so that the chemical reaction is supported. A ventilator is probably helpful.

In areas with thick walls, ash can accumulate that is difficult to remove later. Such material accumulations can even cause local shell cracking. A number of precision-casting foundries, however, have in cooperation with the model makers, managed to control this process so reliably that for every polycarbonate model presented, a casting model is returned. The advent of CastForm PS should solve these problems once and for all.

Following the basic principles of laser sintering, machines have been designed that differ especially in the details, the target applications, and consequently in the materials used. At first some of the constructive solutions were devised owing to the patent situation, but later they prevailed and blazed the way forward.

5.5 Print technologies: extrusion-based print

5.5.1 Extrusion Processes

5.5.1.1 Extrusion Processes

The extruded processes have become known as fused deposition modeling, but this is a trademark of the manufacturer Stratasys. The generic name is extrusion process or in English fused layer modeling (FLM).

The extrusion processes belong to the well-known thermal plastic-extrusion processes and include variants that operate with pastes or foams that are physically or chemically processed from solid basic materials.

Of particular importance are the thermal extrusion processes. The applied volume solidifies through thermal conduction into the component. The method is well suited for materials with low thermal conductivity such as waxes and plastics, including higher melting material like polysulfide. Theoretically, there is no limitation on the usable materials. Practically it requires high melting temperatures, both in terms of melting and of temperature gradients on the model. The required preheating and isolation of the workspace also take correspondingly higher mechanical engineering effort. It is a fully 3D-capable process, depending only on the control of the nozzle because the material supply and material application are done by one nozzle. The relatively large cross section of material limits the achievable degree of detail of the models. With a suitable machine design, these disadvantages can be reduced as far as possible.

A satisfactory joining between the extruded hot material and the already finished part of the model takes place only when the material is "crimped." The circular cross section of the material is applied to an ellipse. Then the balance of volume and surface forces can be set up so that the smoothest possible connection is reachable. This requires that the nozzle axis must always be in the z plane and also includes a specific procedural angle with the x-y plane.

The application of an extruded viscous volume includes the problem that the extruded strand has a beginning and an end. When the contour is closed, a joint line results (Figure 4-8). The lines are particularly noticeable when they are at each layer at the same location.

For the extrusion process a number of interesting plastics were developed, which are like most common construction materials, including ABS and polyphenylsulfone (PPSF), the first high-performance plastic for additive manufacturing. The materials often available in colors so that components can be produced in different colors.

The processes require supports that have to be constructed onto the component and removed after the building process. There are different user-friendly solutions for removing the supports, such as breaking off or detaching in warm water. In this case, the support material is usually a water-soluble wax consisting of polyethylene glycol.

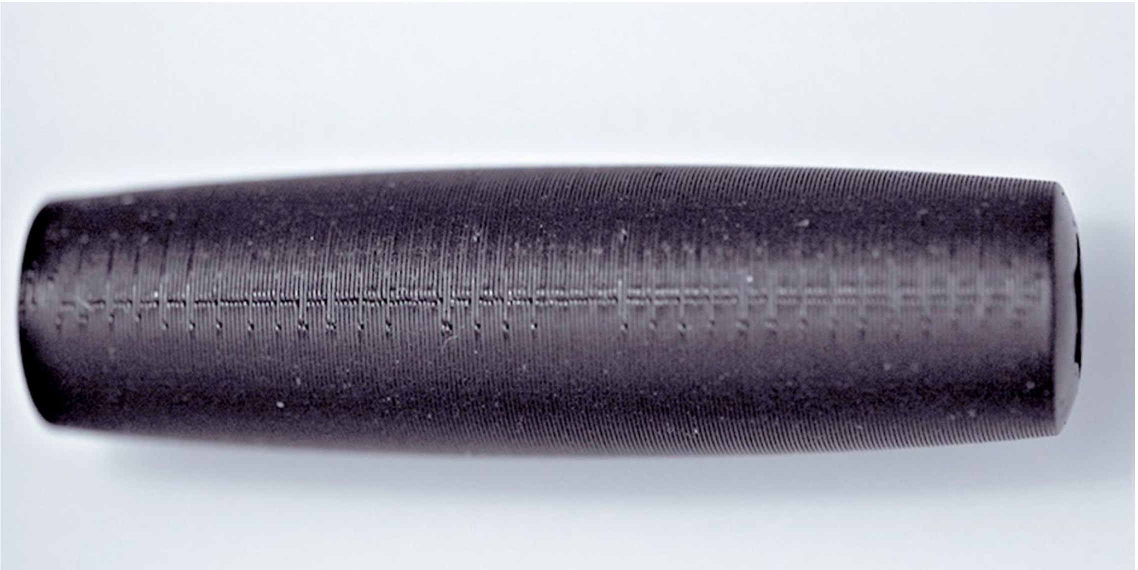


Figure 5-8 - Joint line on extrusion processing. (Source: CP-GmbH/FH-Aachen)

The disadvantage of some machines is the complicated threading of the prefabricated wires. Cassettes for the wire feed and tablets make this procedure easier today.

For fabbers, there is a very large range of cost-effective materials from different manufacturers, which also include nylon and WPC (wood plastic components). Fabbers mostly use the extrusion process and millwork wires made of ABS or PLA, with diameters of usually 0.175 mm or 3 mm. Most of them work with a nozzle and without supports. This limits the manufacturable geometry, particularly in relation to approach angle and undercuts.

5.5.2 Advantages and Disadvantages of Extrusion Processes

5.5.2.1 *Advantages*

The use of single-nozzle extrusion processes enables relatively large amounts to be applied within a relatively short time. The resulting structures are solid. Model materials are used that are very similar or even identical to those series of materials used in later production. The technical realization is comparatively simple. The material is completely used, with no waste. Solvents and similar agents are unnecessary. In contrast to most other rapid prototyping processes, the application of various materials within one construction process, or even one layer, is possible. The number of simultaneously applicable materials is limited only by the fact that the corresponding number of extrusion heads must be fitted geometrically into the machine and controlled by process techniques. The process just uses the material that is necessary for the component. The unprocessed material is within the component, so there is no damage and it remains fully usable.

The process is achievable with machines that can be set up and operated in a variety of environments.

5.5.2.2 *Disadvantages*

The main disadvantage of single-nozzle extrusion is that structures finer than the extrusion width cannot be produced. The same goes for details that, in the extreme case, may not be smaller than double the track width. This means that it is impossible to produce very fine grooves and especially fine ribs. The start of the extrusion always incurs a scab that, depending on the material, remains externally visible even after the contour is closed. Some materials tend to form filaments or condensate. The nozzles tend to clog up, requiring the installation of a suitable cleaning mechanism. The components are very rough and have pronounced anisotropies, especially for the low-price machines and fabbers, due to the large nozzle cross section.

5.5.3 Process Description

The FDM machines from Stratasys melt prefabricated wire-shaped thermoplastics and lead the viscous melt through a heated nozzle specifically to the component. The stratification is done by solidification due to heat conduction in the partially finished component. The range of materials includes plastics such as polycarbonate and ABS, but also high-performance thermoplastic plastics such as polyphenylsulfones (PPSFS). The design principle can be seen in Figure 4-9.

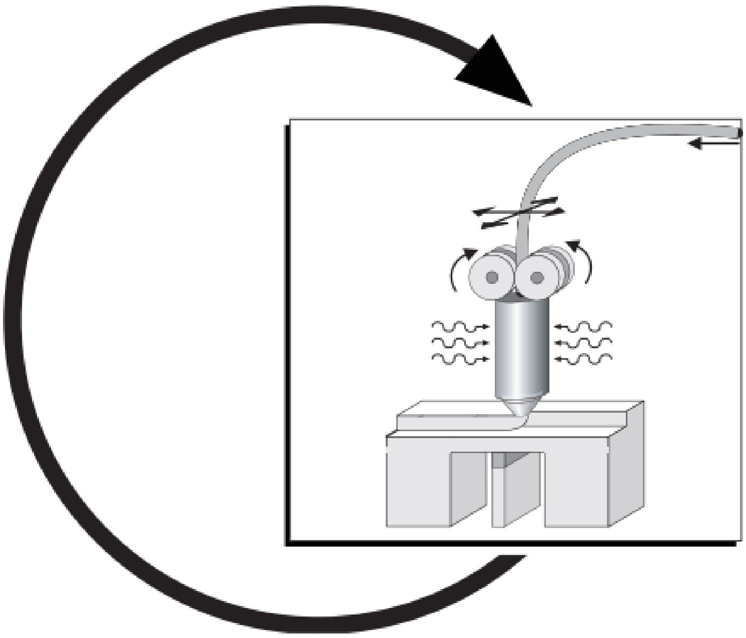


Figure 5-9 - Fused deposition modeling (FDM) scheme

5.5.3.1 Principle of Layer Generation

In this case, the thermoplastics and waxes are supplied in the form of wire on rolls or cartridges, are melted partially, and are extruded (see Figure 4-9). The nozzle head is guided by an x-y plotter in the building plane. After coating a building plane, the base plate with the model is lowered by a layer thickness, and the process begins anew with the next layer.

The raw material is heated in an electrically heated nozzle head to just below melting temperature (about 68 $°C$ for investment casting wax and about 270 $°C$ for ABS plastic) and joins the viscous material to the previous layer (or the first layer on the base plate). It is melted slightly, cools on contact because of heat conduction, and solidifies. The distance between the previous layer and the extrusion head, as well as the volume flow of the semiliquid material, are coordinated so that gauges result from 0.254 to 2.54 mm and layer thicknesses from 0.127 to 0.330 mm. The nozzle head gap is set to the previous layer to about half of the nozzle diameter. This results in a slightly oval fluid cross section whose main dimension is referred to as the row width (RW). This extruded strand width must always be greater than or equal to the layer thickness. Optimal layers are cross sections with a width-toheight ratio between 3.5 and 6. By this "crimping" of the layer, solid structures and relatively smooth surfaces arise as a function of surface tension and viscosity (as a function of temperature). Clearly visible sausage-like structures are thereby weakened in their effect, see Figure 4-10.

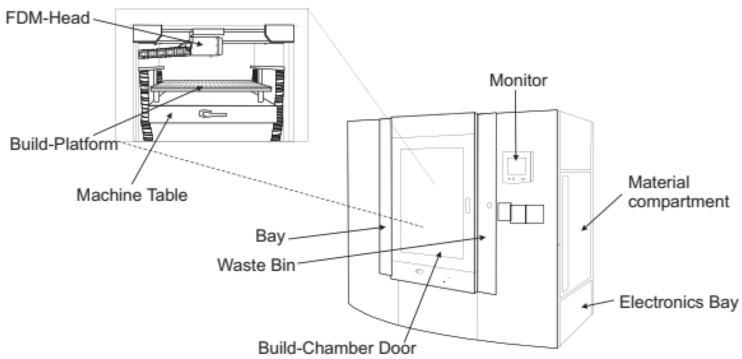


Figure 5-10 - FDM Maxxum, overview with detailed view of processing chambers (Source: Stratasys)

Although the material solidifies very quickly, supports are necessary for projecting sections and for the model as a base. The fully automatically generated columns are made of a more brittle material than the component. Therefore, the supports can be quickly removed without damaging the model and without tools by breaking by hand. This Breakaway Support System (BASS) method is available for the polycarbonate families PC, PC-ISO, and polyphenylsulfones (PPSF). A support material called Water Works (WW) can be removed automatically in a washing station. This support material is for ABS, ABSi, and PC-ABS and continues to spread, despite more and more safety requirements.

The entire component has to be supported with supports. The line spacing for the generation of restraints is half the track width of the next component generated. The angles are specified by the x axis in the clockwise direction. The zero point of the system lies in the left front corner platform.

The nozzle head moves in the components usually below a main direction of 45°, wherein the main direction from layer to layer is changed by ±90° in each case. Since the supports are generated under half of this angle, this angle is usually at about 22.5°. All angles can be changed in the software.

The starting point of each layer can be moved automatically by the software. It is visible and builds up if it is always in the same location as seam on. However, it can be relatively easily abraded. The construction parameters are adjustable in the z direction and on individual regions of each component.

During the building, on the outer sides of the component, a radius is created on the outer corners. The radius is created automatically. In practice, the components must always be provided with a borderline. The borderline is composed of circular elements that arise outside a radius for geometric reasons. Inner contours are automatically always sharply displayed (Figure 4-11).

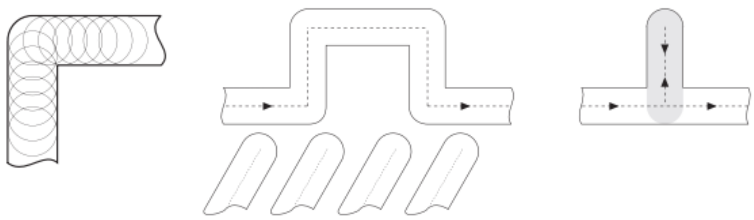


Figure 5-11 - Fused deposition modeling: (a) corner figure; (b) intricate geometric detail;(c) fine webs

The problem is the zone in which the geometry is very delicate. The border is inset by half the row width in the component, similar to the beam compensation in stereolithography, creating areas that cannot be fully passed by a border (Figure 4-11(b)). The vectors are only calculated in the borderlines, therefore thin structures are not displayed. This can be changed manually by breaking the dataset (island) and calculating it with parameters.

The worst case forms a wall, which terminates outside of the component, and the wall thickness is track width. The ideal line in the middle would be crossed double on the way there and back, resulting in an unclean surface (Figure 4-11 (b)). The construction process is not interrupted in this case. Figure 4-12 shows an FDM functional model of the material ABS.

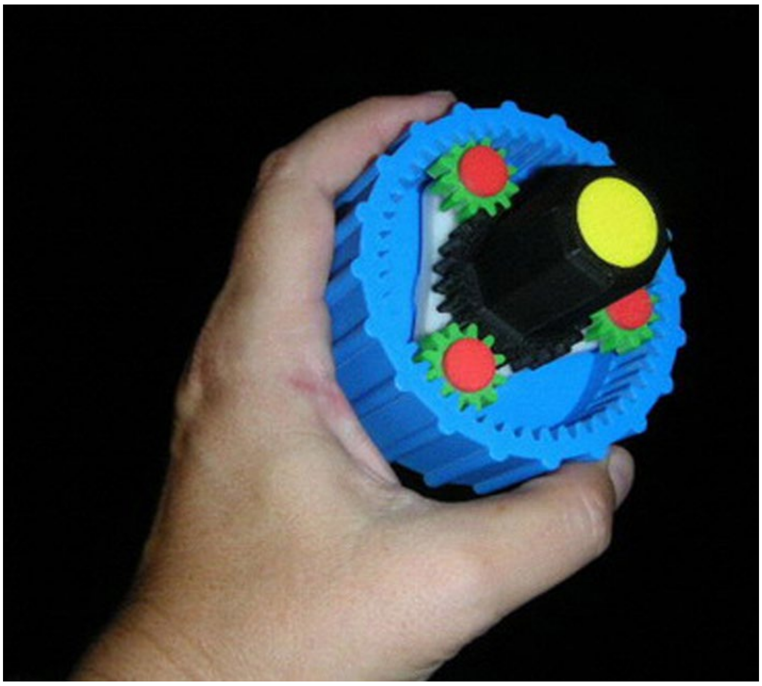


Figure 5-12 - Fused deposition modeling, colored ABS functional model (Source: Stratasys)

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6 3D PRINTING MATERIALS

6.1 Introduction

The materials used for 3D printing are as diverse as the products that result from the process. As such, 3D printing is flexible enough to allow manufacturers to determine the shape, texture and strength of a product. Best of all, these qualities can be achieved with far fewer steps than what is typically required in traditional means of production. Moreover, these products can be made with various types of 3D printing materials. A recently released 3D-printing market study found that the worldwide market for 3D-printing products was valued at $12.6 billion in 2020 and was expected to grow to $37.2 billion by 2036. That means a huge increase in the materials those machines use.[1]

One of the most basic and important knowledge that professionals need so as to comprehend successfully the utilization of 3D printing, is the categories of the most common 3D printing materials, their characteristics and the recommended use for each one of them. In this Learning Unit learners will be able to identify the most popular materials used in 3D printing, their applications, distinct characteristics as well as the pros and cons. In the last chapter a comparison of filament properties and 3D printing materials will be developed.

6.2 Plastic

Learning outcomes:

- Learners will be able to identify the characteristics and application of plastic in 3D printing
- Learners will be familiar with the advantages and disadvantages of plastic
-

Out of all the raw materials for 3D printing in use today, plastic is the most common. Plastic is one of the most diverse materials for 3D-printed toys and household fixtures. Products made with this technique include desk utensils, vases and action figures. Available in transparent

[1] https://redshift.autodesk.com/what-materials-are-used-in-3d-printing/

Co-funded by the
Erasmus+ Programme
of the European Union

form as well as bright colours — of which red and lime green are particularly popular — plastic filaments are sold on spools and can have either a matte or shiny texture.

With its firmness, flexibility, smoothness and bright range of colour options, the appeal of plastic is easy to understand. As a relatively affordable option, plastic is generally light on the pocketbooks of creators and consumers alike.

Plastic still reigns supreme in the 3D printing. According to a Grand View Research report, the market size for 3D printing plastics globally was valued at $638.7 million in 2020 and was expected to grow to $2.83 billion by 2027.

Plastic products are generally made with FDM printers, in which thermoplastic filaments are melted and molded into shape, layer by layer. The types of plastic used in this process are usually made from one of the following materials:

6.2.1 Polyastic acid (PLA)

One of the eco-friendliest options for 3D printers, polyastic acid is sourced from natural products like sugar cane and corn starch and is therefore biodegradable. Available in soft and hard forms, plastics made from polyastic acid are expected to dominate the 3D printing industry in the coming years. Hard PLA is the stronger and therefore more ideal material for a broader range of products. PLA is a great first material to use as you are learning about 3D printing because it is easy to print, very inexpensive, and creates parts that can be used for a wide variety of applications. Because PLA is easier to print with than ABS it is usually the preferred option for low-cost 3D printers. It sticks well to a base covered in white glue or blue painter's tape, meaning a heated print bed is not needed.

Common Applications

- Test and calibration items
- Dimensionally accurate assemblies
- Decorative Parts
- Cosplay Props

Pros	Cons
Low cost	Low heat resistance
Stiff and good strength	Can ooze and may need cooling fans
Good dimensional accuracy	Filament can get brittle and break

6.3 Acrylonitrile butadiene styrene (ABS)

ABS (Acrylonitrile Butadiene Styrene) has a long history in the 3D printing world. This material was one of the first plastics to be used with industrial 3D printers. Many years later, ABS is still a very popular material thanks to its low cost and good mechanical properties. ABS is known for its toughness and impact resistance, allowing you to print durable parts that will hold up to extra usage and wear. Valued for its strength and safety, ABS is a popular option for home-based 3D printers. Alternately referred to as "LEGO plastic," the material consists of pasta-like filaments that give ABS its firmness and flexibility. ABS is available in various colors that make the material suitable for products like stickers and toys. Increasingly popular among craftspeople, ABC is also used to make jewelry and vases.

Common Applications

- Cases or Project Enclosures
- Toys or Action Figures
- Automotive hardware

Pros	Cons
Low cost	Heavy warping
Good impact and wear resistance	Needs heated bed or heated chamber
Less oozing and stringing gives models smoother finish	Produces a pungent odor while printing

6.3.1 Polyvinyl Alcohol Plastic (PVA)

Polyvinyl Alcohol is a newer class of 3D printing material used for making supports that hold 3D prints in place. It is a synthetic polymer and is water soluble. It melts at about 200 degrees C and releases some pretty unpleasant chemicals when heated to high temperatures. Used in low-end home printers, PVA is a suitable plastic for support materials of the dissolvable variety. Though not suitable for products that require high strength, PVA can be a low-cost option for temporary-use items.

Common Applications
- Removable supports or rafts
- Dissolvable/Disintegratable applications
- Decorative parts

Pros	Cons
Great water dissolvable support material No special solvents required No additional hardware required	Moisture sensitive Airtight storage containers required Greater chances of clogging if the nozzle is left hot when not extruding Expensive

6.3.2 Polycarbonate (PC)

Less frequently used than the aforementioned plastic types, polycarbonate only works in 3D printers that feature nozzle designs and that operate at high temperatures. Among other things, polycarbonate is used to make low-cost plastic fasteners and molding trays. Polycarbonate (PC) is a high strength material intended for tough environments and engineering applications.

Common Applications
- High-strength parts
- Heat resistant prints
- Electronics cases

Pros	Cons
Impact resistant High heat resistance Naturally transparent	Requires very high print temperatures Prone to warping High tendency to ooze while printing Absorbs moisture from the air which can cause print defects

6.4 Powders

Learning outcomes:

- Learners will be able to identify the characteristics and application of powders in 3D printing
- Learners will be familiar with the advantages and disadvantages of powders

Today's more state-of-the-art 3D printers use powdered materials to construct products. Inside the printer, the powder is melted and distributed in layers until the desired thickness, texture and patterns are made. The powders can come from various sources and materials, but the most common are:

6.4.1 Polyamide (Nylon)

With its strength and flexibility, polyamide allows for high levels of detail on a 3D-printed product. The material is especially suited for joining pieces and interlocking parts in a 3D-printed model. Polyamide is used to print everything from fasteners and handles to toy cars and figures.

Common Applications

- Plastic Gears
- Screws, nuts, bolts
- Cable ties

Pros	Cons
Tough and partially flexible	Prone to Warping
High impact resistance	Air-tight storage required to prevent water absorption
No unpleasant odor while printing	Improperly dried filaments can cause printing defects
Good abrasion resistance	Not suitable for moist and humid environments

6.5 Alumide

Comprised of a mix of polyamide and gray aluminum, alumide powder makes for some of the strongest 3D-printed models. Recognized by its grainy and sandy appearance, the powder is reliable for industrial models and prototypes.

6.6 Resins

Learning outcomes:

- Learners will be able to identify the characteristics and application of resins in 3D printing
- Learners will be familiar with the advantages and disadvantages of resins

One of the more limiting and therefore less-used materials in 3D printing is resin. Compared to other 3D-applicable materials, resin offers limited flexibility and strength. Made of liquid polymer, resin reaches its end state with exposure to UV light. Resin is generally found in black, white and transparent varieties, but certain printed items have also been produced in orange, red, blue and green.

The material comes in the following three categories:

- **High-detail resins**: Generally used for small models that require intricate detail. For example, four-inch figurines with complex wardrobe and facial details are often printed with this grade of resin.
- **Paintable resin**: Sometimes used in smooth-surface 3D prints, resins in this class are noted for their aesthetic appeal. Figurines with rendered facial details, such as fairies, are often made of paintable resin.
- **Transparent resin**: This is the strongest class of resin and therefore the most suitable for a range of 3D-printed products. Often used for models that must be smother to the touch and transparent in appearance. Transparent resins of clear and coloured varieties are used to make figurines, chess pieces, rings and small household accessories and fixtures.

Distinct characteristics:

- It can be used in many applications.
- It has low shrinkage.
- Resin materials have high chemical resistance.
- This material is rigid and delicate.

Disadvantages:

- It is expensive.
- This type of filament also expires.
- It needs to be stored securely due to its high photo-reactivity.
- When exposed to heat, it can cause premature polymerization.

6.7 Metal

Learning outcomes:

- Learners will be able to identify the characteristics and application of metal in 3D printing
- Learners will be familiar with the advantages and disadvantages of metal

The second-most-popular material in the industry of 3D printing is metal, which is used through a process known as direct metal laser sintering or DMLS. This technique has already been embraced by manufacturers of air-travel equipment who have used metal 3D printing to speed up and simplify the construction of component parts. DMLS printers have also caught on with makers of jewelry products, which can be produced much faster and in larger quantities — all without the long hours of painstakingly detailed work — with 3D printing.

Metal can produce a stronger and arguably more diverse array of everyday items. Jewelers have used steel and copper to produce engraved bracelets on 3D printers. One of the main advantages of this process is that the engraving work is handled by the printer. As such, bracelets can be finished by the box-load in just a few mechanically programmed steps that do not involve the hands-on labor that engraving work once required.

The technology for metal-based 3D printing is also opening doors for machine manufacturers to ultimately use DMLS to produce at speeds and volumes that would be impossible with current assembly equipment. Supporters of these developments believe 3D printing would allow machine-makers to produce metal parts with strength superior to conventional parts that consist of refined metals.

The range of metals that are applicable to the DMLS technique is just as diverse as the various 3D printer plastic types:

- Stainless-steel: Ideal for printing out utensils, cookware and other items that could ultimately come into contact with water.
- Bronze: Can be used to make vases and other fixtures.
- Gold: Ideal for printed rings, earrings, bracelets and necklaces.
- Nickel: Suitable for the printing of coins.
- Aluminum: Ideal for thin metal objects.
- Titanium: The preferred choice for strong, solid fixtures.

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Common Applications
- Sculptures and Busts
- Replicas for Museums
- Jewelry

Pros	Cons
Metallic finish is aesthetically appealing	Requires a wear-resistant nozzle
Does not need high-temperature extruder	Printed parts are very brittle
Heavier than standard filaments	Very poor bridging and overhangs
	Can cause partial clogs over time
	Expensive

6.8 Carbon Fiber

Learning outcomes:

- Learners will be able to identify the characteristics and application of carbon fiber in 3D printing
- Learners will be familiar with the advantages and disadvantages of carbon fiber

Composites such as carbon fiber are used in 3D printers as a top-coat over plastic materials. The purpose is to make the plastic stronger. The combination of carbon fiber over plastic has been used in the 3D printing industry as a fast, convenient alternative to metal. In the future, 3D carbon fiber printing is expected to replace the much slower process of carbon-fiber layup.

With the use of conductive carbomorph, manufacturers can reduce the number of steps required to assemble electromechanical devices.

Common Applications
- R/C Vehicles
- Functional prototypes
- Decorative pieces
- Lightweight Props

Pros	Cons
Increased strength and stiffness	Abrasive and requires hardened steel nozzle
Very good dimensional stability	Increased oozing while printing
Lightweight	Increased brittleness of filament
	Higher tendency to clog

6.9 Graphite And Graphene

Learning outcomes:

- Learners will be able to identify the characteristics and application of graphite and graphene in 3D printing
- Learners will be familiar with the advantages and disadvantages of graphite and graphene

Graphene has become a popular choice for 3D printing because of its strength and conductivity. The material is ideal for device parts that need to be flexible, such as touchscreens. Graphene is also used for solar panels and building parts. Proponents of the graphene option claim it is one of the most flexible of 3D-applicable materials.

The use of graphene in printing received its largest boost through a partnership between the 3D Group and Kibaran Resources, an Australian mining company. The pure carbon, which was first discovered in 2004, has proven to be the most electrically conductive material in laboratory tests. Graphene is light yet strong, which makes it the suitable material for a range of products.

6.10 Wood

Learning outcomes:

- Learners will be able to identify the characteristics and application of wood in 3D printing
- Learners will be familiar with the advantages and disadvantages of wood

Wood-based filaments are typically a composite that combines a PLA base material with wood dust, cork, and other powdered wood derivatives. Typically, the filament consists of around 30% wood particles, but the exact number may vary depending on the brand. The presence of these particles gives the 3D printed parts the aesthetics of real wood. This filament is also less abrasive compared to other composite filaments such as carbon-fiber filled and metal filled, since wood particles are much softer. There are some wood-like filaments on the market that only contain wood coloring, but no actual wood particles, so these typically have a very different look and feel.

Common Applications

- Household decorations
- Cosplay props
- Toys

Pros	Cons
Wood-textured finish is aesthetically appealing	Prone to stringing
Does not need any expensive wear resistant nozzles	Smaller nozzles can end up with partial clogs over time
Aromatic and pleasant smelling	May require a larger size nozzle

6.11 Hips

Learning outcomes:

- Learners will be able to identify the characteristics and application of HIPS in 3D printing
- Learners will be familiar with the advantages and disadvantages of HIPS

HIPS, or High Impact Polystyrene, is a dissolvable support material that is commonly used with ABS. When being used as a support material, HIPS can be dissolved in d-Limonene, leaving your print free of any markings caused by support removal. HIPS has many of the same printing properties as ABS, making it a logical dual extrusion partner. Not only is HIPS great for supporting your ABS prints, it's also more dimensionally stable and slightly lighter than ABS, making it a great choice for parts that would end up getting worn out or used in applications that can benefit from the lighter weight.

Common Applications

- Dissolvable Support Material for ABS
- Cosplay & Wearables
- Protective Cases

Pros	Cons
Low cost	Heated bed required
Impact and water resistant	Heated chamber recommended
Lightweight	High printing temperature
Dissolvable by d-Limonene	Ventilation required

6.12 PETG

Learning outcomes:

- Learners will be able to identify the characteristics and application of PETG in 3D printing
- Learners will be familiar with the advantages and disadvantages of PETG

PETG is a Glycol Modified version of Polyethylene Terephthalate (PET), which is commonly used to manufacture water bottles. It is a semi-rigid material with good impact resistance, but it has a slightly softer surface which makes it prone to wear. The material also benefits from great thermal characteristics, allowing the plastic to cool efficiently with almost negligible warpage. There are several variations of this material in the market including PETG, PETE, and PETT. The tips in this article will apply to all of these PET-based filaments.

Common Applications

- Water proof applications
- Snap fit components
- Planter Pot

Pros	Cons
Glossy and smooth surface finish	Poor bridging characteristics
Adheres well to the bed with negligible warping	Can produce thin hairs on the surface from stringing
Mostly odorless while printing	

6.13 3D printing materials compared

Learning outcomes:

- Learners will be able to identify the best 3D printing material based on the needs
- Learners will be familiar with the advantages and disadvantages of the most common 3D printing materials

This table summarizes a wide variety of properties and characteristics for each material.

	ABS	PLA	HIPS	PETG	Nylon	Carbon Fiber Filled	Polycarbonate	Metal Filled	Wood Filled	PVA
	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More
Compare Selected Show All										
Ultimate Strength	40 MPa	65 MPa	32 MPa	53 MPa	40 - 85 MPa	45 - 48 MPa	72 MPa	20 - 30 MPa	46 MPa	78 MPa
Stiffness	5 / 10	7.5 / 10	10 / 10	5 / 10	5 / 10	10 / 10	6 / 10	10 / 10	8 / 10	3 / 10
Durability	8 / 10	4 / 10	7 / 10	8 / 10	10 / 10	3 / 10	10 / 10	4 / 10	3 / 10	7 / 10
Maximum Service Temperature	98 °C	52 °C	100 °C	73 °C	80 - 95 °C	52 °C	121 °C	52 °C	52 °C	75 °C
Coefficient of Thermal Expansion	90 µm/m-°C	68 µm/m-°C	80 µm/m-°C	60 µm/m-°C	95 µm/m-°C	57.5 µm/m-°C	69 µm/m-°C	33.75 µm/m-°C	30.5 µm/m-°C	85 µm/m-°C
Density	1.04 g/cm^3	1.24 g/cm^3	1.03 - 1.04 g/cm^3	1.23 g/cm^3	1.06 - 1.14 g/cm^3	1.3 g/cm^3	1.2 g/cm^3	2 - 4 g/cm^3	1.15 - 1.25 g/cm^3	1.23 g/cm^3
Price (per kg)	$10 - $40	$10 - $40	$24 - $32	$20 - $60	$25 - $65	$30 - $80	$40 - $75	$50 - $120	$25 - $55	$40 - $110
Printability	8 / 10	9 / 10	6 / 10	9 / 10	8 / 10	8 / 10	6 / 10	7 / 10	8 / 10	5 / 10
Extruder Temperature	220 - 250 °C	190 - 220 °C	230 - 245 °C	230 - 250 °C	220 - 270 °C	200 - 230 °C	260 - 310 °C	190 - 220 °C	190 - 220 °C	185 - 200 °C
Bed temperature	95 - 110 °C	45 - 60 °C	100 - 115 °C	75 - 90 °C	70 - 90 °C	45 - 60 °C	80 - 120 °C	45 - 60 °C	45 - 60 °C	45 - 60 °C
Heated Bed	Required	Optional	Required	Required	Required	Optional	Required	Optional	Optional	Required
Recommended Build Surfaces	Kapton Tape, ABS Slurry	Painter's Tape, Glue Stick, Glass Plate, PEI	Glass Plate, Glue Stick, Kapton Tape	Glue Stick, Painter's Tape	Glue Stick, PEI	Painter's Tape, Glue Stick, Glass Plate, PEI	PEI, Commercial Adhesive, Glue Stick	Painter's Tape, Glue Stick, PEI	Painter's Tape, Glue Stick, PEI	PEI, Painter's Tape
Other Hardware Requirements	Heated Bed, Enclosure Recommended	Part Cooling Fan	Heated Bed, Enclosure Recommended	Heated Bed, Part Cooling Fan	Heated Bed, Enclosure Recommended, May Require All Metal Hotend	Part Cooling Fan	Heated Bed, Enclosure Recommended, All Metal Hotend	Wear Resistant or Stainless Steel Nozzle, Part Cooling Fan	Part Cooling Fan	Heated Bed, Part Cooling Fan

Figure 6-1 - Filament Properties Table https://www.simplify3d.com/support/materials-guide/properties-table/?filas=abs,pla,hips,petg,nylon,carbon-fiber-filled,polycarbonate,metal-filled,wood-filled,pva

Choosing the right type of material to print a given object is becoming increasingly difficult, as the 3D Printing market sees the regular emergence of radically new materials. In FDM 3D Printing , PLA and ABS have historically been the two main polymers used, but their initial dominance was mostly fortuitous, so there should not be any major roadblocks for other polymers to play a key role in the future of FDM.

We are now seeing new products become more popular, both pure polymers and composites. In this study, we focus on the main pure polymers that exist in the market today: PLA, ABS, PET, Nylon, TPU (Flexible) and PC.

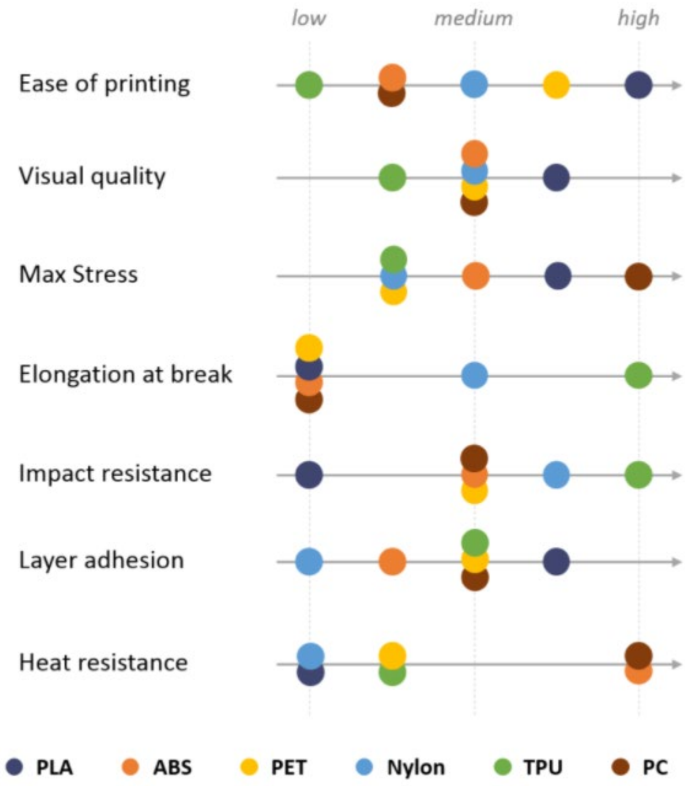

Figure 6-2 – Material properties

With proper knowledge equipped and the right materials being used, industrial 3D printing can be done efficiently. As the 3D printing industry grows, more and more materials will be used for making prototypes and will be compatible with different 3D printers. As with any new processes and equipment there is a steep learning curve and this increases as you move from plastic to metal 3D Printing.

6.14 References

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7 SAMPLE STL CODES FOR AUTOMOTIVE TECHNOLOGY EDUCATION

7.1 Oil filter removal tool

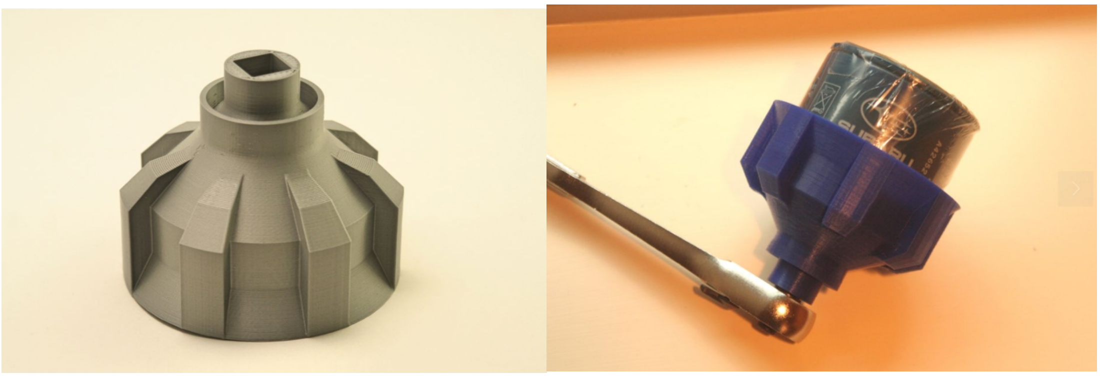


Figure 7-1 – Oil filter removal tool

This is an oil filter removal tool designed to divert and funnel excess oil through the tool and out the bottom. This is helpful for oil filters that are mounted vertically. When removing filter, excess oil would run down the side of the filter and get all over my hand which made it really hard to hold and unscrew the filter (especially if the oil was still hot). This tool has channels in the side which route the excess oil though the inside of the tool and reduces the mess.

The flow channels provide extra grip for removing the filter.

The funnel hole at the bottom fits a 1/2 ratchet wrench just in case the filter is really stuck on there. Note: the wrench needs to be removed after loosening the filter since the wrench will block the drain hole.

The tool acts as a general funnel as well. The end of the tool/funnel fits nicely inside the opening of a 1 Liter or 4 Liter oil container. This keeps the tool/funnel stable while pouring the old oil back in the containers. Note: the size of the container opening somewhat differs between brands so it might not fit for all oil containers.

7.1.1 Print Settings

Printer: Custom built "PrintrMatic"

Rafts: No

Supports: No

Resolution: 0.2 - 0.25

Infill: 75-100%

STL files (download)

oil_filter_drain_V02.STL

oil_filter_drain_6.35mm_V00.STL

oil_filter_drain_72.5mm_V00.STL

oil_filter_drain_V01-OLD.STL

7.2 Push Pin Clip/Push Rivet

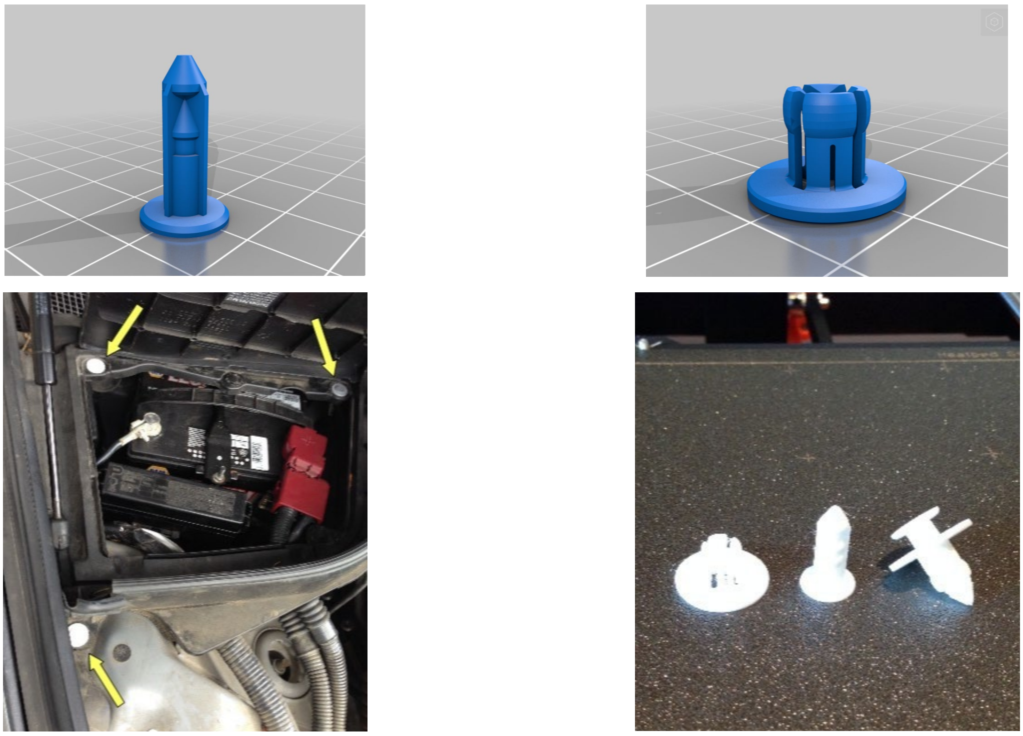


Figure 7-2 – Push Pin clip CAD model and print (right) and Push Rivet CAD model and print (left)

Replacement part for push pin clips. Printed with PETG filament. Consider them single or maybe two-use. There are two versions of the retainer part of the clip. One with slots for theoretically easier bending of the tabs, the other without slots. For nylon, definitely use the without slots.

These are neat fasteners, also known as "Push Rivets." You can assemble the clip before installation, by pushing the pin in until the first "click," or you can inset the retainer into the hole first, then insert the pin and push down flush.

This retaining clip is sized for an 8mm hole and can accommodate 5mm depth. The flange is 20mm. Added a 16mm flange version for more flexibility with sizing/scaling.

7.2.1 Print Settings

Printer: Prusa i3 MK3

Resolution: 0.2

Infill: 100% rectilinear

STL files (download)

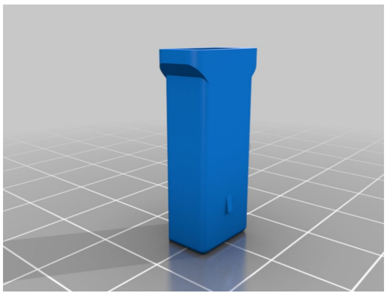
Pin_for20mmFlange.stl

Pin_for16mmFlange.stl

Retainer_20mmFlange.stl

Retainer_16mmFlange.stl

7.3 Connectors



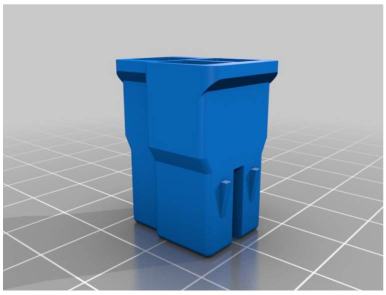


Figure 7-3 – Electrical Connectors CAD models

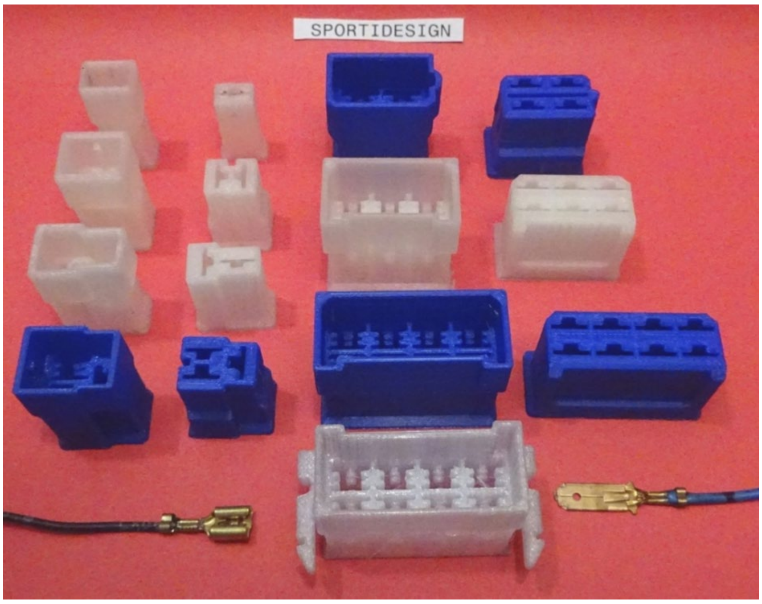


Figure 7-4 - Electrical Connectors print

Electrical Car connectors 1- to 8-way for especially 12–24-volt applications.

The design is based on the FASTIN-FASTON connectors series 250 from TYCO (TE Connections), formerly AMP.

They have been used for decades in most cars, trucks and caravans and many other applications to this day and were among the first electrical corner connectors designed for this purpose.

These connectors are designed to be compatible as spare parts, but additionally optimized for 3D printing.

The associated contacts, flat receptacles 6.3 (¼ inch) and plugs 6.3 are also among the most widely used contacts.

If the assembly of the contacts in the cavities should be a little difficult, so you can help with a flat pliers on the cable / crimp a little. The contacts must lock with an audible click.

They can be removed from the Cavity by pressing back the latching tab with a watchmaker's screwdriver and pulling it out of the cavity.

Application for 48 volts is still possible, for 110 volts, 240 Volts and more in no case.

The material to be used should be as heat resistant as possible, since a lot of heat can be generated in the connector in addition to the ambient temperatures. PLA should not be used, better PETG/ ABS or best NYLON.

A support is not necessary, except for the connector housings 6 and 8-pole with latching arms for the printed circuit board. Rafts can also be omitted. Layer spacing 0.2 works, but less is better.

7.3.1 Print Settings

Printer: Dremel Digilab 3D45

Rafts: No

Supports: No

Resolution: 0,2mm max

Infill: 100%

STL files (download)

Female-Housing-1-way.stl

Male-Housing-3-way.stl

Male-Housing-2-way-Typ-1.stl

Male-Housing-8-way-Typ-2.stl

Male-Housing-4-way.stl

Male-Housing-1-way.stl

Female-Housing-2-way-Typ-1.stl

Female-Housing-3-way.stl

Male-Housing-2-way-Typ-2.stl

Male-Housing-6-way-Typ2.stl

Male-Housing-8-way-Typ-1.stl

Female-Housing-4-way.stl

Female-Housing-2-way-Typ-2.stl

Female-Housing-6-way.stl

Male-Housing-6-way-Typ-1.stl

Female-Housing-8-way.stl

7.4 Measuring tire groove

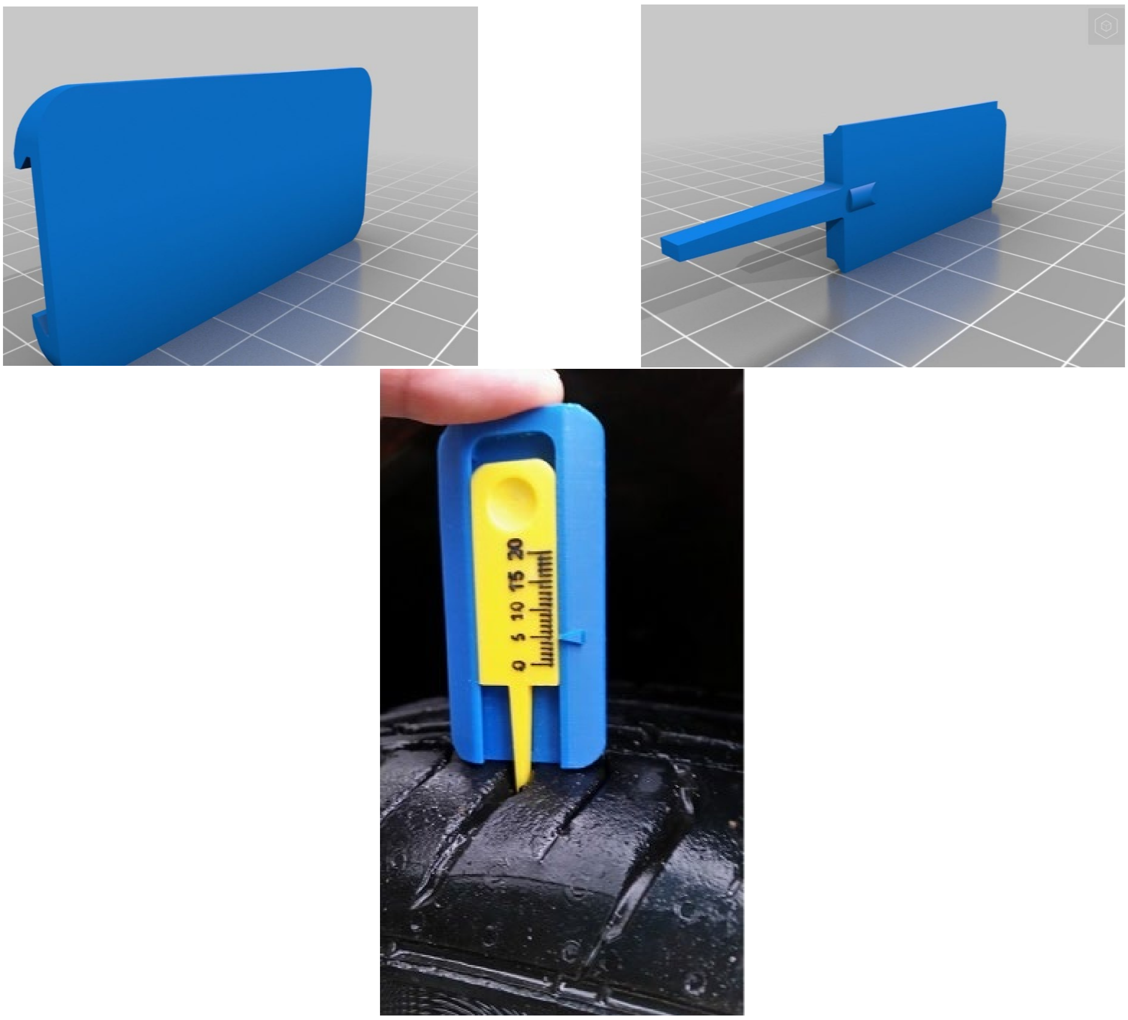


Figure 7-5 – Measuring tire groove CAD models and print

7.4.1 Print Settings

Printer: Zortrax M200

Rafts: Yes

Supports: Yes

Resolution: 0,09 mm

Infill: 100%

STL files (download)

Based.STL

Measured.STL

7.5 Relay holder

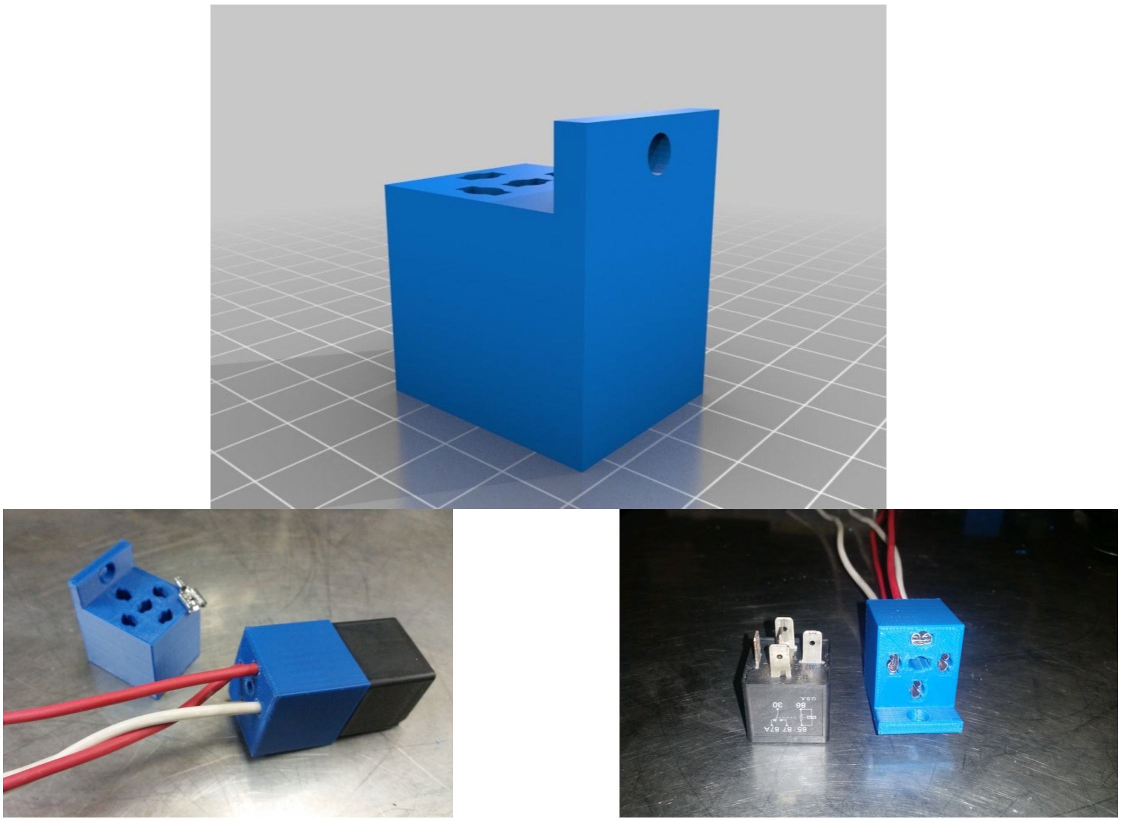


Figure 7-6 – Relay holder CAD models and prints

Relay and socket harness for 5 or 4 pin standard automotive relay. standard naked female blade terminals can be crimped to wires and pushed through the block from the top. The blades may need a slight tweaking once pressed in to allow the blade on the relay to fit easily. It may be hard to get it to seal at first but once it conforms to the block it will install and remove easily with the terminals remaining in the block. The design included has a mount bracket that can be used to attach it to anything. Edit the file if you like and make a custom relay box.

7.5.1 Print Settings

Printer: PowerSpec 3D Pro

Supports: No

Resolution: 0,09 mm

Infill: 8 to 20%

STL files (download)

RelaySocketCR.stl

7.6 Trim removal tool

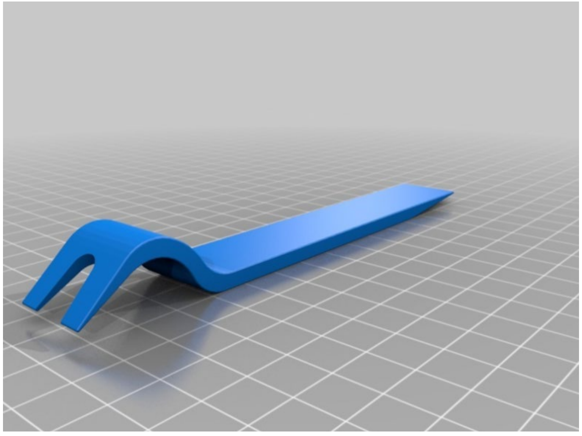


Figure 7-7 – Trim removal tool CAD model and print

Car door clip panel pry and removal tool. The tool is 4mm thick by 20mm tall and about 145mm in length. The clip tine opening is 6.5mm at its narrowest and about 9mm at its widest.

7.6.1 Print Settings

Printer: Geetech

Supports: Yes

Infill: 99%

STL files (download)

BUM_CAR_TOOLS_6001_upholstery_fork_and_pry.STL

BUM_CAR_TOOLS_6001_upholstery_ fork_and_pry_-_smaller_file_size.STL

7.7 Fuse tool

Quick printable 12V car fuse holder.

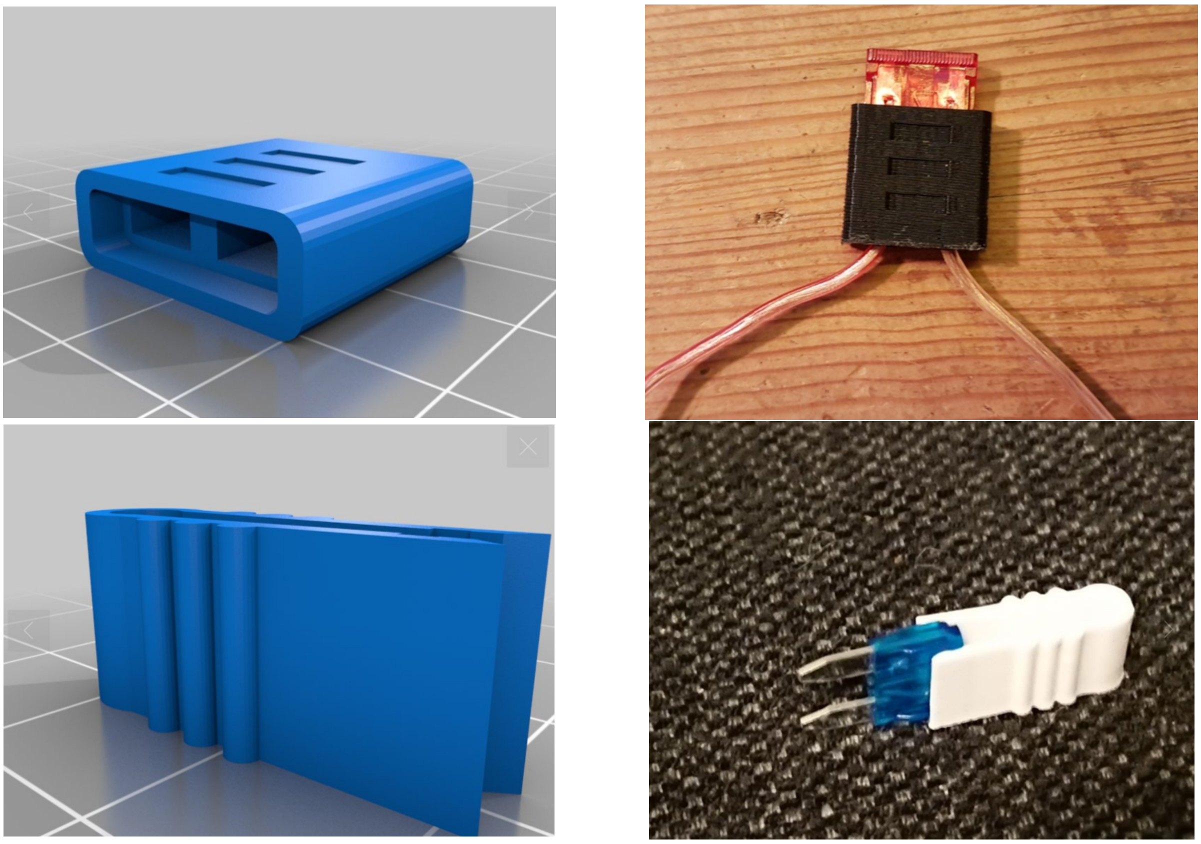


Figure 7-8 – Fuse tools: CAD models on the left and prints on the right

7.7.1 Print Settings

Printer: Anet A8

Rafts: Yes

Supports: No

Resolution: 0,20 mm

Infill: 30%

STL files (download)

single_fuse_holder.stl

MiniFuse.stl

7.8 Gearbox

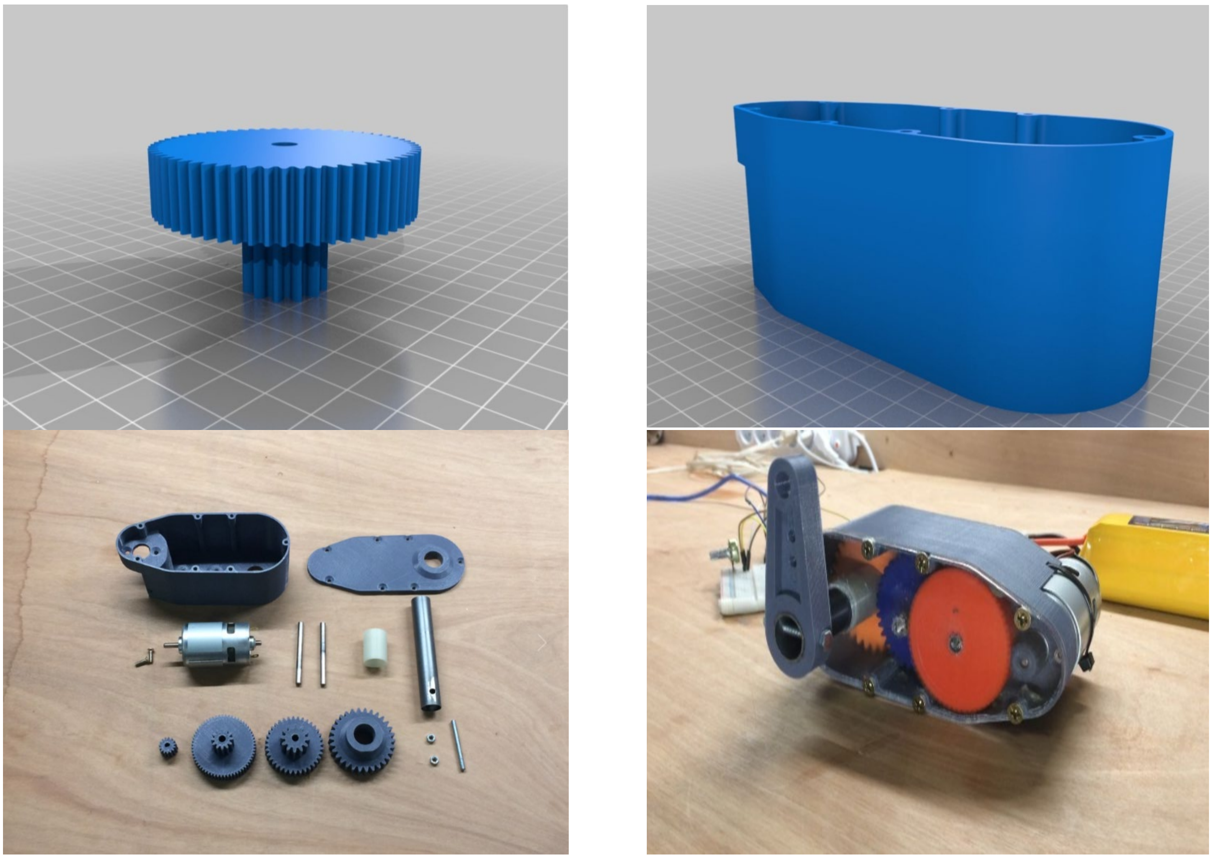


Figure 7-9 – Gearbox CAD models and prints

This servo/gear reduction uses mostly 3D-printed parts. The servo uses a 775 36V 9000rpm brushed DC-motor which is driven by a BTS7960B motor driver which is controlled by an Arduino mega 2560. The stall torque of the servo is about 55kg/cm which is about 5.39 Nm. the peak current is about 18 amps when using a 6s LIPO battery (about 22-24V). the reduction ratio is 1:30.

7.8.1 Components used:

1 × 775 Motor DC 12V-36V 3500-9000RPM Motor Large Torque High Power Motor

1 × Arduino nano V3

1 × L298N motor driver

1 × Heat shrinks

2 × stainless steel shaft

2 × M5 bolt and nut

1 × 20mm steel tube

2 × screws 15mm lenght

5 × screws 35mm length

7.8.2 Print Settings

Printer: Anet E12

Supports: Yes

Resolution: 0,20 mm

Infill: 35%

STL files (download)

33mm_spacer_V1.stl

Co-funded by the
Erasmus+ Programme
of the European Union

servo_arm_V1.stl

Lid_V2.stl

Spur_Gear_15_teeth_motor_V1.stl

Spur_Gear_30_teeth_output_shaft_V1.stl

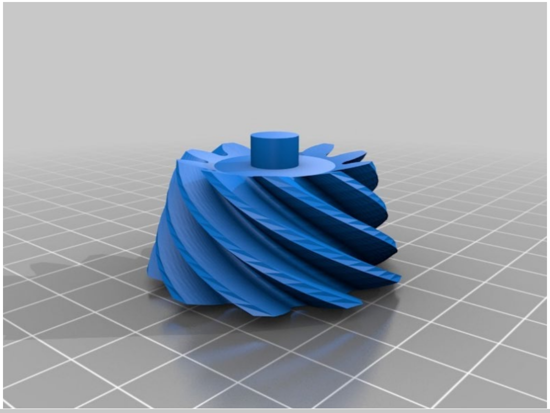
Spur_Gear_60-12_teeth_V1.stl

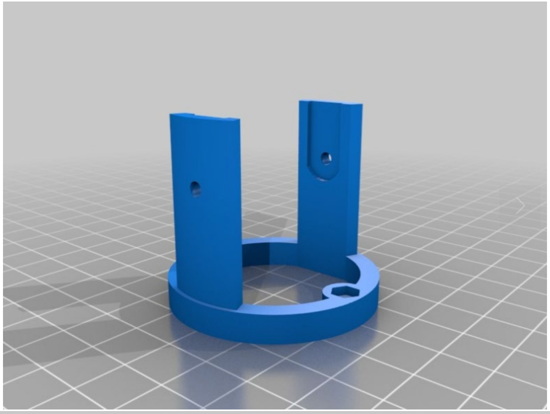
Spur_Gear_36-12_teeth_V1.stl

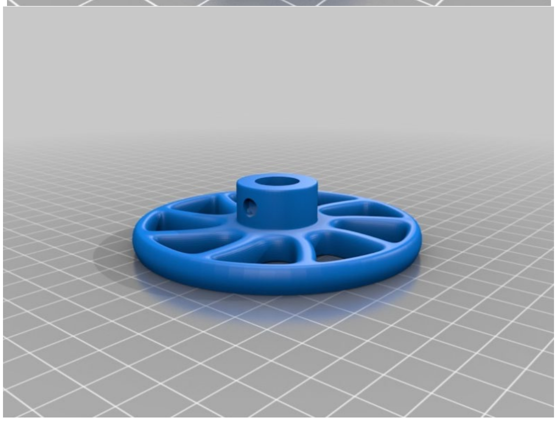
775_servo_lid.dxf

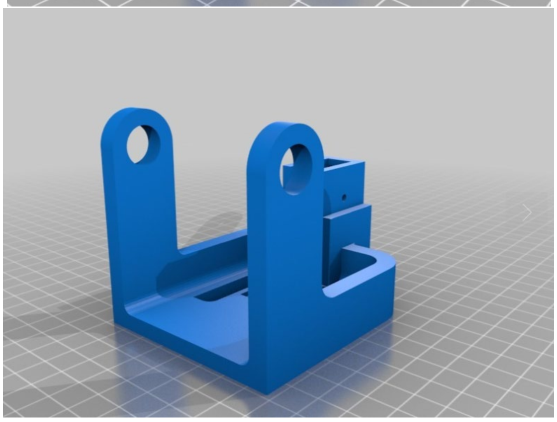
Case_V3.stl

7.9 Automotive Differential









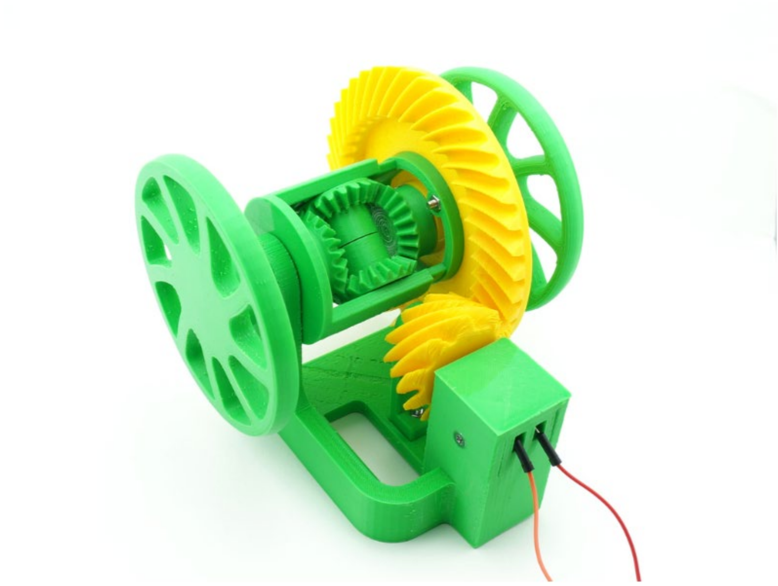


Figure 7-10 – Automotive differential; CAD models and print

The automotive differential is something every automobile has: this ingenious mechanism transmits power from the drive shaft at 90° to the driving wheels, while allowing them to rotate at different speeds when the driving conditions call for it, such as during a turn.

This is a motorized model of the most basic kind of automotive differentials, known as the open differential. Unlike most 3D-printable differential models out there, this one is equipped with a hypoid, not bevel, pinion/ring gear pair.

The model is powered by a 6V electric motor equipped with a speed reducer. It requires an external power source, such as four AA batteries in a holder, or an old 6V phone charger with stripped wires.

Please visit http://www.otvinta.com/download09.html for detailed and illustrated assembly instructions.

The pinion needs ample support to ensure smooth meshing with the ring gear. We use Simplify3D and had to add support manually to cover all teeth, No other part needs support beyond the default amount.

You need to print 2 wheels, 2 side gears, 2 spider gears, and 1 of all other parts.

7.9.1 Print Settings

Printer: MakerGear M2

Rafts: No

Supports: Yes

Resolution: 0,20 mm

Infill: 35%

STL files (download)

diff_spider_shaft.stl

diff_leftshaft.stl

diff_carrier.stl

diff_carrier_cover.stl

diff_stand.stl

diff_rightshaft.stl

diff_arm.stl

diff_pinion.stl

diff_motor_cover.stl

diff_side.stl

diff_spider.stl

diff_ring.stl

diff_wheel.stl

7.10 Resources:

https://www.thingiverse.com/thing:1135889

https://www.thingiverse.com/thing:3490414

https://www.thingiverse.com/thing:5174925

https://www.thingiverse.com/thing:2317645

https://www.thingiverse.com/thing:1977671

https://www.thingiverse.com/thing:1748810

https://www.thingiverse.com/thing:3095801

https://www.thingiverse.com/thing:4205535

https://www.thingiverse.com/thing:3292860

https://www.thingiverse.com/thing:2116304

8 Evaluation Tests

8.1 Unit 1 Evaluation Test

1) Stereolithography is commonly known as:
   a. 3D printing
   b. 2D printing
   c. Mould production technology
   d. Model production technology

2) The first person to file a patent for Rapid Prototyping Technology was:
   a. Dr. Hideo Kodama
   b. Charles Hull
   c. Scott Crump
   d. Lis Crump

3) The mass expansion of 3D printing can be dated from
   a. 2015
   b. 2009
   c. 1989
   d. 2011

4) FFF (FDM) is a method of:
   a. Where plastic nickel wire does not melt
   b. Where the steel wire is melted
   c. Where the plastic wire melts
   d. Where the copper wire is melted

5) Patents for FDM (FFF) technology expired in

a. 2009
b. 2000
c. 2010
d. 1999

6) The company introduced an Urbee car with a body made using 3D printing
   a. Volkswagen
   b. Chrysler
   c. KOR Ecologic
   d. Mercedes

7) The world's car manufacturers incorporated HP Metal Jet 3D printers in:
   a. 1995
   b. 2020
   c. 2000
   d. 2018

8) One car consists of:
   a. 6,000-8,000 parts
   b. 1,000-3,000 parts
   c. 3,000-4,000 parts
   d. 2,000-3,000 parts

9) The DARWIN printer had the ability to:
   a. Self-replication
   b. Self-regulation

10) MakerBot Academy is a platform whose content is:
   a. Training in working with 3D printing in schools in Germany.

b. Training in working with 3D printing in schools in the USA.
c. Training for working with 3D printing in schools in Poland
d. Professional training for working with 3D printing in schools in Slovakia

8.2 Unit 2 Evaluation Test

1) What is the name of the part of extruder that allows for the filament to be heated and ready for the extrusion process?
   a. Cold end
   b. Print Bed
   c. Thermistor
   d. hot end

2) What type of filament given below is biodegradable and has a melting point relatively less than the others?
   a. Nylon
   b. ABS
   c. PLA
   d. TPE

3) What part of the 3D printers given below are used to measure the temperature in different parts of the 3D printers?
   a. Cold end
   b. Hot end
   c. Thermistor
   d. Nozzle

4) What part of the 3D printer given below is responsible for turning electric current into heat?
   a. Heater Cartridge
   b. Filament
   c. Thermistor
   d. Power Supply

5) What part of the 3D printers given below is responsible for the final extrusion of the filament?
    a. Thermistor
    b. Motherboard
    c. Nozzle
    d. Gears

6) What is the name of the system that allows for 3-dimensional movement of the print head?
    a. Power supply
    b. X, Y, and Z axis
    c. PLA
    d. Heater Cartridge

7) Which part of a 3D printer given below controls the production process and gather relevant data from the other parts?
    a. Nozzle
    b. Heater Cartridge
    c. Power supply
    d. Motherboards

8) Which part given below is the energy unit of 3D printer that usually comes in 12V or 24V?
    a. Nozzle
    b. Thermistor
    c. Power Supply
    d. Stepper Motor

9) What part given below allows users to display the printing process, control the 3D printer, enable standby mode, and perform other functions?
    a. Stepper motor
    b. Heater cartridge
    c. Hot end
    d. User Interface

10) What option given below is one of the functions of stepper drivers?

a. Controlling the movement of stepper motors
b. Extrusion of the filament
c. Displaying the data about the 3D printer on the screen
d. Measuring the temperature at the nozzle

8.3 Unit 3 Evaluation Test

1) This unit 3 will focus on…

a. Assembling a 3D Printer
b. The printing process.
c. The creation of objects in a virtual environment.
d. Exporting files of 3D objects.

2) After completing the training of unit 3, it is expected…

a. To know the main commands to design objects in 3D.
b. To be capable of creating a picture of an object.
c. To know and execute some hand-drawing techniques.
d. To recognize and understand the functions of the object.

3) 3D Drawing is the ability…

a. Of printing a 3D object.
b. Of drawing shapes defining the object's height, width and depth.
c. Of recognizing different types of filaments.
d. A, B, and C are wrong.

4) In which of the following areas we can see 3D Drawing in use nowadays?

a. Civil Construction.
b. Architecture.
c. Graphics Design.
d. A, B, and C are correct.

5) What kind of software is OnShape?
   a. It is a real-time data management software.
   b. It is a professional CAD software (SaaS).
   c. It is the most popular 3D shapes and objects database.
   d. It is a text processor.

6) After completing our 3D drawing on OnShape, it is possible to…
   a. Export it to an STL file.
   b. Export it to a GCode file.
   c. Export it to both formats.
   d. A, B, and C are wrong.

7) In a 3D drawing, it is recommended to start by…
   a. Extruding an element and shaping it after.
   b. Performing the 3D design and, afterwards, adding 2D details.
   c. Designing a 2D sketch with all the main and possible details and extrude it after.
   d. Drawing a rectangle.

8) What is the main feature of an STL file?
   a. Transfer the information to our 3D Printer.
   b. Retrieve the information from Ultimaker Cura.
   c. Transfer the information to OnShape.
   d. Transfer the user's design information to the slicing software.

9) The Ultimaker Cura is…
   a. A slicing software.
   b. A converter software.
   c. A professional 3D Design software.
   d. A professional and the most popular printing software.

10) After performing the slicing process, we must…

a. Download the STL file and send it to the 3D Printer.
b. Download the GCode file and send it to the Printing Software.
c. Download the GCode file and send it to the 3D Printer.
d. Download the STL file and send it to the Printing Software.

8.4 Unit 4 Evaluation Test

1) What does slicing process do?

a. A slicing process separates CAD model into layers.
b. A slicing process separates CAD model into triangle pyramids.
c. A slicing process makes STL type file.
d. A slicing process makes tessellation.

2) What is a tessellation process?

a. Tessellation is an approximation process of 3D shape of the CAD model with round patches.
b. Tessellation is an approximation process of 3D shape of the CAD model with planar triangular patches.
c. Tessellation is an approximation process of 3D shape of the CAD model with rectangular patches.
d. Tessellation is an approximation process of 3D shape of the CAD model with hexagonal patches.

3) Which is the way for calculating layer parameters?

a. A technician calculates all layer parameters.
b. An engineer calculates all layer parameters.
c. The algorithm of a slicing technique calculates all layer parameters.
d. The manager of a company calculates all layer parameters.

4) What are the input data for the algorithm of a slicing technique?

a. CAD model data are input data for the algorithms.
b. Part data from drawing are input data for the algorithms.

c. CAM data of a CAD model are input data for the algorithms.
d. CAD model data after tessellation are input data for the algorithms.

5) What does a uniform slicing process separate?
   a. A uniform slicing process separates the CAD model into uniform thickness layers.
   b. A uniform slicing process separates the CAD model into two parts.
   c. A uniform slicing process separates the CAD model into several varies thickness layers.
   d. A uniform slicing process separates the CAD model into several vertical parts.

6) How is extracted profile of each layer?
   a. By connecting of every line formed between intersecting points of triangle edges and the cutting plane.
   b. By connecting of every triangle edge intersecting the cutting plane.
   c. By connecting of every triangle edge which do not intersect the cutting plane.
   d. By connecting of every line formed by connecting the highest Z vertex of triangles intersecting the cutting plane.

7) Why stair-step effect occurs?
   a. Stair-step effect occurs due to various contours of each slice.
   b. Stair-step effect occurs due to original shape of CAD model.
   c. Stair-step effect occurs due to 3D printer performance.
   d. Stair-step effect occurs due to wrong position of 3Dmodel.

8) What contradicting issues has led to the development of number of slicing procedures.
   a. Reduction in build time and better surface quality.
   b. Original shape of CAD model and tessellated CAD model.
   c. Cartesian coordinate system and Polar coordinate system.
   d. Metal materials and plastic materials.

9) What is the concept of adaptive slicing?
   a. The concept of adaptive slicing is cusp height tolerance.

b. The concept of adaptive slicing is to slice tessellated CAD model to various slice thickness between maximum and minimum thickness available.
c. The concept of adaptive slicing is isotropic physical property.
d. The concept of adaptive slicing is better view of printed part.

10) What is direct slicing?
a. Generating slice data directly from CAD software.
b. Slicing the CAD model to avoid stair-step effect.
c. Slicing the original CAD model shape.
d. Producing the part in slices.

8.5 Unit 5 Evaluation Test

1) Which is the source that allows resin solidification in Stereolithography:
a. Heat
b. Flame
c. Laser
d. High temperature Resistance

2) As far as concerns FDM printers, the movement of the printing head is driven by a plotter moving:
a. Along x axis only
b. Along y axis only
c. Along all the three dimensions (x, y, z)
d. In the x-y Cartesian plane

3) FDM printed object show rough (relatively) surface finishing; one of the most noticeable scab happens at the beginning of the contouring. This effect is called:
a. Joint line
b. Interlock
c. Scattering
d. This effect is not noticeable in FDM print process

4) FDM printing process is one of the most versatile; nevertheless, one of the most important drawbacks is the overall and surface print quality. The main reason to this disadvantage is:
   a. It is not possible to produce structures finer than the extrusion width
   b. The material quality
   c. The printing temperature
   d. The plate movement

5) Laser Sintering process:
   a. Requires support structures for the printed part
   b. Does not require support structures for the printed part
   c. Produce support structures in any case
   d. Produce support structure only for cave pieces

6) Stereolithography realizes the solidification of a layer with a sequence of consolidated spots-called:
   a. Pixels
   b. Voxels
   c. Galvo points
   d. Hot points

7) In Stereolithography processes one of the post-processing phases is called:
   a. UV postcure phase
   b. Heating
   c. UV washing phase
   d. Thermal surface finishing

8) In plastic powder-based Laser sintering processes, the first post-process operation is:
   a. Milling
   b. Solvent washing the component
   c. Taking out the component and blowing it off with compressed air or brushing
   d. Rinsing the component with water

9) In order to print hollow components recurring to stereolithography:
   a. The model must have openings through which the noncross-linked monomer may leak
   b. The model mustn't have double convexity surfaces
   c. The model must be planar
   d. It is not possible to print hollow model with stereolithography

10) The component created with laser sintering processes are:
   a. Shiny and dense
   b. Dense
   c. Porous
   d. Stepped

8.6 Unit 6 Evaluation Test

1) Which 3D printing material is most eco-friendly?
   a. PVA
   b. Metal
   c. Nylon
   d. PLA

2) Which 3D printing material has the highest durability?
   a. ABS
   b. PC
   c. Wood
   d. PETG

3) Which 3D printing material is NOT heat resistant?
   a. ABS
   b. HIPS
   c. Nylon
   d. PVA

4) The process DMLS with which 3D printing material is used?
   a. PC
   b. Carbon fiber
   c. Metal
   d. Graphite

5) How can we make the plastic stronger?
   a. Use a heated bed
   b. Use carbon fiber as a top-coat
   c. Use a thermoforming process
   d. Immerse it in water

6) If the item you want to develop needs to be detailed which material is best to use?
   a. PLA
   b. HIPS
   c. ABS
   d. Nylon

7) Which 3D printing material is connected with the picture  ?
   a. ABS
   b. PVA
   c. PC
   d. HIPS

8) Which of the 3D printing materials is usually a composite?
   a. Plastic
   b. Metal
   c. Wood
   d. Graphite

9) What is the most common material used for 3d printing?
    a. Plastic
    b. Metal
    c. HIPS
    d. Nylon

10) With the use of which material, manufacturers can reduce the number of steps required to assemble electromechanical devices?
    a. Conductive carbomorph
    b. Graphene
    c. Stainless-steel
    d. Titanium

8.7 Unit 7 Evaluation Test

1) The STL format defines:
    a. Texture of an object in three dimensions
    b. Colour of an object in three dimensions
    c. Dimensions of an object in three dimensions
    d. Surface geometry of an object in three dimensions

2) STL is a numerical representation consisting of:
    a. A mosaic of triangles, each of which has a known position of its three vertices
    b. A mosaic of cubes, each of which has a known position of its four edges vertices.
    c. A mosaic of spheres, each of which has a known position of its canter.
    d. A mosaic of tetrahedra, each of which has a known position of its four edges.

3) Warping is a common problem in 3D printing; it occurs when the first layer of molten plastic cools too quickly and begins to contract causing the corners of the model to retort upwards. Which of the following options is not a possible solution to the problem?

a. Use a heated print bed
b. Increase the adhesion of the first layer on the printing plate
c. Use a heated print bed
d. Make sure the build plate level is calibrated well

4) Which of the following are signs that your printing temperature is too low:
   a. Parts printed in PLA have a very glossy surface
   b. Poor layer adhesion
   c. Excessive spillage while the nozzle is stationary
   d. Bubbles or cloudiness in extruded yarns also with dry filament

5) Which of the following software allows STL file repair?
   a. Paint 3D
   b. Blender
   c. Netflix
   d. Cura

6) What does the use of STL software entail?
   a. The definition of all print parameters according to the object and printer
   b. Greater definition of the 3D model
   c. Defines the colour of the object to print
   d. Defines the geometric shape of the object to be printed

7) When you need to print multiple parts what do you need to check?
   a. The extruder temperature
   b. The temperature of the plate
   c. The colour of the filament
   d. The relative size of the parts

8) Increasing the print speed, you get ...
   a. Higher quality of the finished product
   b. Lower quality of finished product
   c. A higher layer height
   d. A lower layer height

9) Once all the setting operations are complete, what does the generated G-Code file represent?
   a. Only instructions for setting the extruder temperature
   b. Only the instructions for the storage of layers
   c. The entire set of instructions for setting the printer and for depositing the layers
   d. Just one way to run a printer diagnostic test

10) What characteristics of the object to be printed cannot be defined by the CURA software?
   a. Layer height
   b. Shell thickness
   c. Colour
   d. Fill density