Universidad de Valladolid

ESCUELA DE INGENIERÍAS INDUSTRIALES

UNIVERSIDAD DE VALLADOLID

ESCUELA DE INGENIERIAS INDUSTRIALES

Grado en Ingeniería Mecánica

3D printer redesign to start with granulate plastic

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Valladolid, julio de 2016.

TFG REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO: 3D printer redesign to start with granulate plastic

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Resumen y palabras clave (Abstract y Keywords):

El proyecto gira en torno al rediseño de una impresora 3D existente con el objetivo de que el plástico inicial se encuentre en forma de gránulos en lugar de su apariencia más común: filamento de 1,75 mm de diámetro. En ambos casos el material al que nos referimos es PLA. Esta decisión está fundamentada en el precio del material inicial y en la versatilidad del nuevo aspecto del mismo. Durante el proyecto se busca la forma mas viable teóricamente para rediseñar una impresora que cumpla las prestaciones mencionadas. Para ello se proponen diferentes soluciones y, tras quedarnos con la mas viable, se calculan los parámetros necesarios para que sigan con valores aproximados a los de la máquina existente, a modo de referencia. Se deja como trabajo futuro construirla para probar si de verdad es viable, así como ampliar el rango de materiales a poder ser utilizados.

– Rediseño.
– Extrusión.
– Temperaura.
– Materiales.
– Parámetros de funcionamiento.

Content

1. Introduction

A couple of years ago, 3D printing technology emerged as the newest, cheapest and most challenging process for the future, but at that point there was an uncertain atmosphere within all the technological community. With the pass of the time, it has been shown that all the expectations around 3D printing had been covered and even more, that what it exists nowadays is nothing if comparing with all the technological advance that it could be created in the next years.

As it continues being a new technology, a lot of work and researches have to be done in this field and this is why we are trying to help the 3D printing processes development to reach its maximun abarcable goal as soon as possible. All the researchers want to reach this point in order to be able to render virtual 3D models into real ones with the cheapest technology found for the moment and taking into account that most if the materials used in it come from recycling them.

Although this technology has evolved a lot since it was discovered, as the access to 3D printers is becoming easier because the prices are going down and nowadays both companies and regular users can develop their own parts in a relatively simply and accessible way, there are some specific fields inside the 3D printing world that hadn't already been developed that much. And this is where our project wants to take place, in one of the fields with less researchers, the 3D printing processes beginning with plastic granulates.

So, this memory contains the information and researches done to propose a design of a new head for the 3D printers. This design has its main particularity in allowing to print using plastic granulate instead of the filament original plastic shape commonly used. The aim of the project is to propose a new design of a functional 3D printer head that overcome some limitations of the filament based process like the need for a thermoplastic filament as feed material or especially the limited range of commercially available materials which can be processed. In addition, it will be studied the feasibility of this new head comparing with the existing ones, how expensive can it be and which are the benefits and disadvantages of it.

All the work will be done redesigning an existing machine that actually prints filament plastic, but all the research and details evolving the project could be used by anybody that wants to start an investigation in the granulate plastic 3D printing technology.

This project will study the existing world of 3D printing, explaining how its works, the applications it has, the materials that are commonly used and how do the researchers focus their investigation, which is the technology that already exist and which are the fields where this technology can be improved. After this literature study we will focus in the specific goal of the project to propose a head that could replace an existing filament plastic 3D printer head into a granulate plastic one. We will try to be as specific as possible because this project will only cover the theoretical study so in the future the project could be continued by other person with the practical part.

2. Goals

Although the ultimate goal of the project is to design a new head for 3D printer starting from plastic granulate instead of using the filament plastic in order to overcome the limitations that this filament technology has, we will focused our project in achieving it for an existing 3D printing machine placed in Vives university (campus Kortrijk, Belgium) mechanical laboratory. Most of the parts of the project will be done in a general way, so then they could be taken into consideration as help for every research focused in 3D printers starting with granulate plastic material.

What we have just said is the main goal of the project but there are a couple of goals more. The first goal is to introduce to the reader into the 3D printing world by making him knowing the most commonly used processes, the most common materials and in general the existing technology. Other important goal is to make the people conscious that the 3D printing world is just emerging and there are many things than still hadn't been researched as much as they should be.

The last goal we consider is to find a cheaper way to reproduce 3D virtual models into real ones. Of course, 3D printing is much cheaper than many other existing techniques, but we are trying to find the cheapest way inside the 3D printing world. As buying the plastic in granulates is cheaper than in filaments, we are trying to reduce the cost of the initial material because is an important part of the budget after having the 3D printer already constructed.

3. Literature study

First of all, we are going to start explaining briefly the most important aspects and generalities about 3D printing so with it the reader can understand how we proceed with the approach during the project. We will focus the literature study in giving an overview of the existing technology, the existing techniques, everything related with extrusion and the material that we are going to use, that is actually the most used one in 3D printing.

3.1. Additive Manufacturing

3D printing or Additive Manufacturing (AM) is a process consisting on synthesizing a three-dimensional object. In 3D printing, successive layers of material are formed under computer control to create an object. In this point we will explain the different ways to obtain a 3D part to show out the possibilities and to enter in the world of 3D printing in order to understand why has this technology become so important.

Not all the 3D printers use the same technology. There are several ways to print although all of them differ mainly in the way layers are build. Some methods use melting or softening material to produce the layers. Selective laser sintering (SLS) and fused deposition modelling (FDM) are the most common technologies that use this way of printing. Another method of printing is when curing a photo-reactive resin with a UV laser, the most common technology using this method is called Stereolithography (SLA).

Despite the way of 3D printing that we use, the configuration of the solid always starts with the virtual design of the object you want to create. This virtual design is made in a CAD (Computer Aided Design) file using a 3D modeling program. Then this file is sent to another program that slices the model into layers generating a code needed for the printer. In this last program many printing characteristics such as the speed of the machine, the size of the material printed, the roughness,..., could be configured.

Nowadays 3D printing is a well-known technology mostly used in the processes of prototyping due to the simplicity, the price and the speed of the process. Thanks to the increasing interest and technological evolution, 3D printers are starting also to be used for the production of single or small series of functional products.

In general, there are three different categories of additive manufacturing: Selective Binding, Selective Solidification and Selective Deposition. Below we are going to name the main characteristics of them:

- **Selective Binding technologies** make a 3D printed object from a powder (metal and gypsum usually) by applying binding agents or heat to fuse the powder's particles together.

- **Selective Solidification** makes a solid object from a vat of liquid by applying energy to solidify the liquid a layer at a time. The most commonly used technology in this process is Stereolithography (SLA). Typically, a first layer is created on some sort of build platform, which then moves down into the liquid or, in some cases, a build platform pulls up out of the liquid.

- **Selective Deposition techniques** only place material where you want it. Fused deposition modelling (FDM) is the most common technology. During printing, the plastic filament is fed through a hot extruder where the plastic gets soft enough that it can be precisely placed by the print head. These are the most popular machines and the cheapest ones.

However, the American Society for Testing and Materials (ASTM) group has developed a set of standards that classify the additive manufacturing processes into 7 categories:

- Vat Photopolymerisation
- Material Jetting
- Binder Jetting
- Material Extrusion
- Powder Bed Fusion
- Sheet Lamination
- Directed Energy Deposition

3.1.1. Vat Photopolymerization

Vat Polymerization is a method in 3D printing characterized in using a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. Resins are cured using a process of photo polymerisation or UV light. The initial materials for the 3D model in the process are plastics or polymers.

To explain more detailed how does the process work we can name the following steps:

1. The platform is lowered from the top of the resin vat. Every time a layer is down, the platform has to be moved down as much as the layer thickness.
2. An ultraviolet light cures the resin layer by layer. New layers are built on top of the already existing ones.
3. A keen machine provides to every layer a smooth resin base to build the next layer on.
4. When the layers are finished the vat is drained of resin and the object is removed.

In *Figure 1*, we can see the elements that take part in the process:

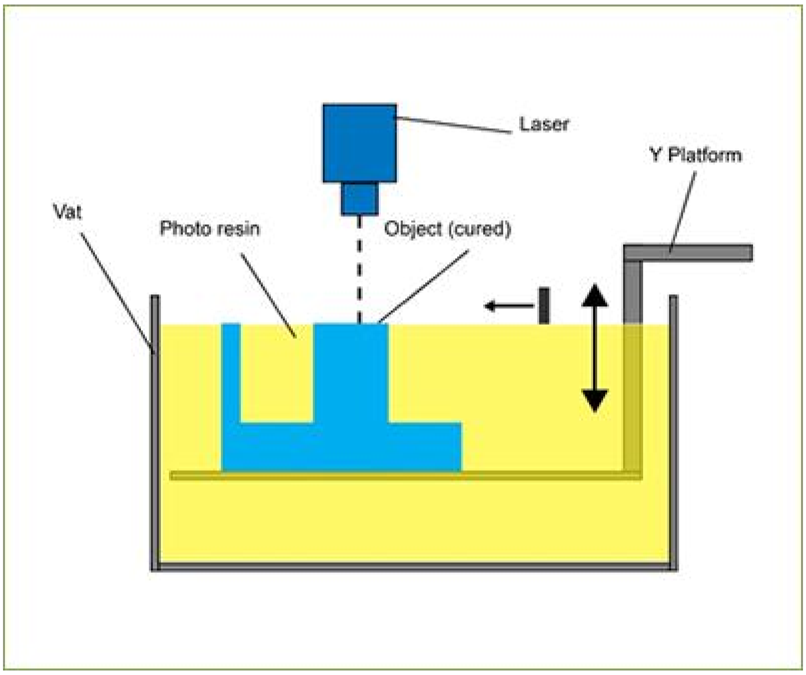

Figure 1. Vat Photopolymerisation process

The advantages of this process is that it is a relatively quick process, despite the lengthly post processing time and removal from resin, with a high level of accuracy and finish. Also it is possible to have large build areas and very heavy objects could be created. In the other hand, it is an expensive process because often requires support structures and post processing. In addition, limited material can be used, only those affected by photo polymerisation.

3.1.2. Material Jetting

Material Jetting, also known as Multijet modelling or Drop on Demand (DOD), is a 3D printing method that creates objects by jetting material onto a build platform. Material jetting machines use inkjet print heads to jet droplets of melted materials, which then cool and solidify. The steps of the process are the following ones:

1. The print head is positioned above the build platform.
2. Droplets of material are deposited from the print head onto surface where required.
3. Droplets of material solidify and make up the first layer.
4. Further layers are built up on top of the previous.
5. Layers are allowed to cool and harden or are cured by UV light.

The process can be easily visualize in the following picture:

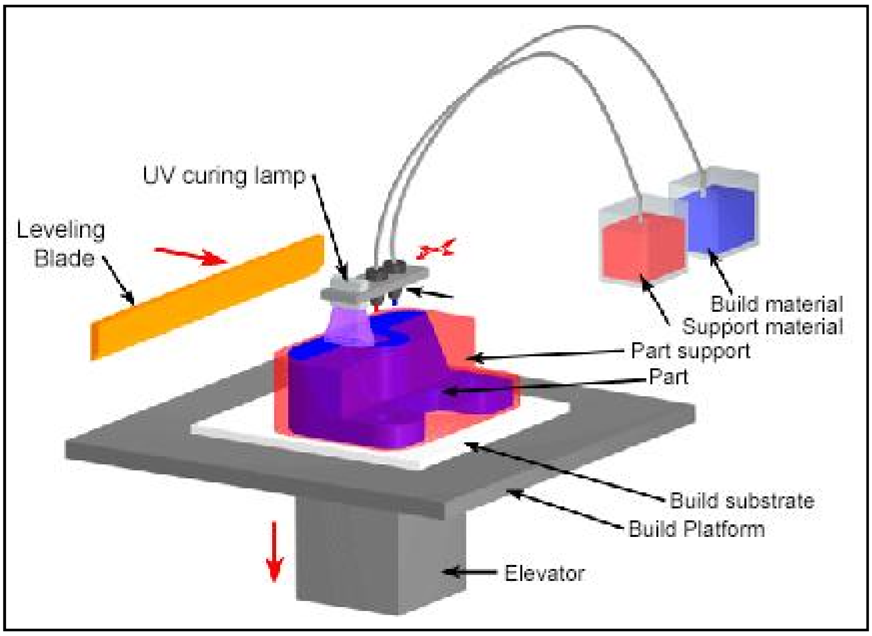

Figure 2. Material Jetting process

The main advantage of this technology is that it can achieve very good accuracy and surface finishes. However, using droplets, limits the number of materials that can be used. Polymers (Polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS, EDP) and waxes are often used due to their viscous nature and ability to form drops. Viscosity is the main determinant in the process; there is a need to re-fill the reservoir quickly and this in turn affects print speed. The process also allows multiple materials and colours due to the multiple jet head. During the post processing, removal of support material is requiered.

3.1.3. Binder Jetting

Binder Jetting, also called 3DP technology, uses materials powder as base material and an adhesive binder which is usually liquid. The process allows metal, polymers and ceramics as base materials. It is generally faster than others because it is easy to increase the number of holes in the head that deposit materials. The two material approach allows for a large number of different binder-powder combinations and various mechanical properties options of the final model to be achieved by changing the ratio and individual properties of the two materials.

However, this process is not always suitable for structural parts because of the binder material. In addition, post processing is often required to make the part stronger and give the binder-material better mechanical and structural properties. So this can increase a lot the time of the process.

The main steps of the process are named below, and the process is shown in *Figure 3*:

1. Powder material is spread over the build platform using a roller to distribute it uniformly.
2. The print head deposits the binder adhesive on top of the powder where required.
3. The build platform is lowered by the model's layer thickness.
4. Another layer of powder is spread over the previous layer. The object is formed where the powder is bound to the liquid.
5. Unbound powder remains in position surrounding the object.
6. The process is repeated until the entire object has been made.

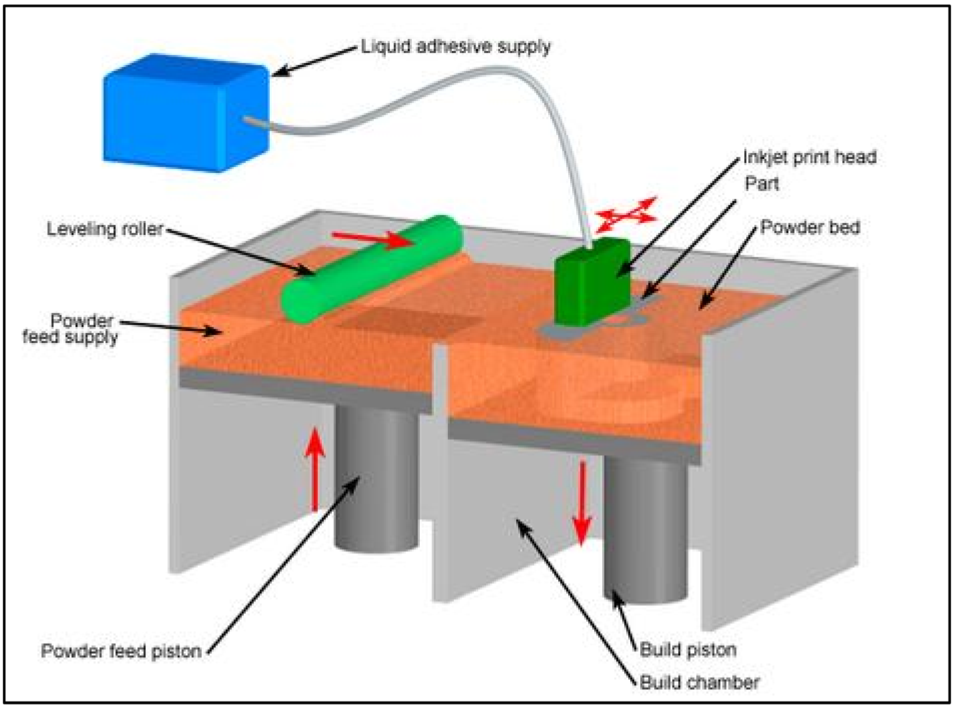

Figure 3. Binder Jetting process

3.1.4. Material Extrusion

Material extrusion is selective deposition process usually associate to the Fused deposition modelling (FDM) technology. The principle of Selective deposition is as simple as building up a piece by adding melted plastic on a flat surface and erect a part layer by layer. It is a commonly used technique used on many domestic 3D printers. The feed material is always polymers or plastics in a wire form, which is drawn through a nozzle in a continuous process and under constant pressure.

The nozzle is heated in order to melt the plastic before it is deposited layer by layer. The nozzle can move horizontally in X and Y axis and up and down in the Z axis, nevertheless is also possible that the nozzle is fixed and is the base plate the motion piece. After a layer is deposited, the nozzle moves up, or the platform moves down.

To sum up the process we can divide it in the following steps:

1. The first layer is built as nozzle deposits material where required onto the cross sectional area of first object slice.
2. The following layers are added on top of previous layers.
3. Layers are fused together upon deposition as the material is in a melted state.

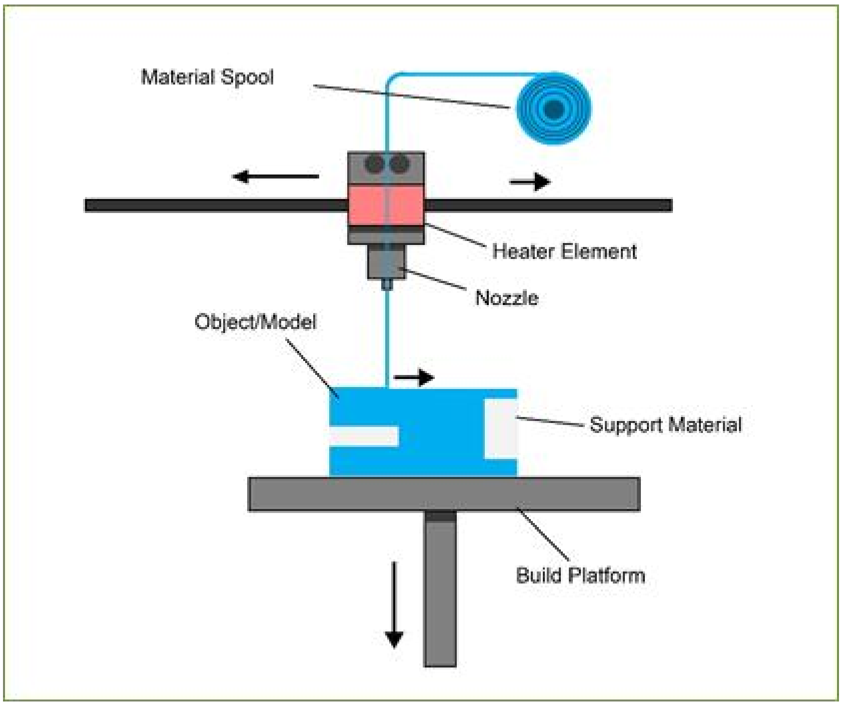

Figure 4. Material Extrusion process

The process is quite inexpensive and it allows a wide range of materials as feed material (ABS, PLA, Nylon, PC, PC, AB). It is also a quick process and it is used in fast prototyping. The disadvantages of FDM are that the accuracy of the final model is low comparing with other processes and also the nozzle radius limits and reduces the final quality.

The existing machine actually uses this process and as we want to keep the maximum elements possible, we are also going to use this process in the redesigned 3D printer, so in the next points we will go further in the explanation of this specific process.

3.1.5. Power Bed Fusion

The Powder Bed Fusion process includes several printing techniques: Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS). All of these techniques may be similar to binder jetting process but using either a laser or electron beam, instead of a binder, to melt and fuse material powder together. Only Selective Heat Sintering (SHS) uses a heated thermal print head to fuse the powder material together.

The process can be clearly explain in the folllowing steps:

1. A layer, around 0.1mm thick, of material is spread over the build platform.
2. A laser fuses the first layer of the model.
3. A new layer of powder is spread across the previous layer using a roller.
4. Further layers are fused and added.
5. The process repeats until the entire model is created.

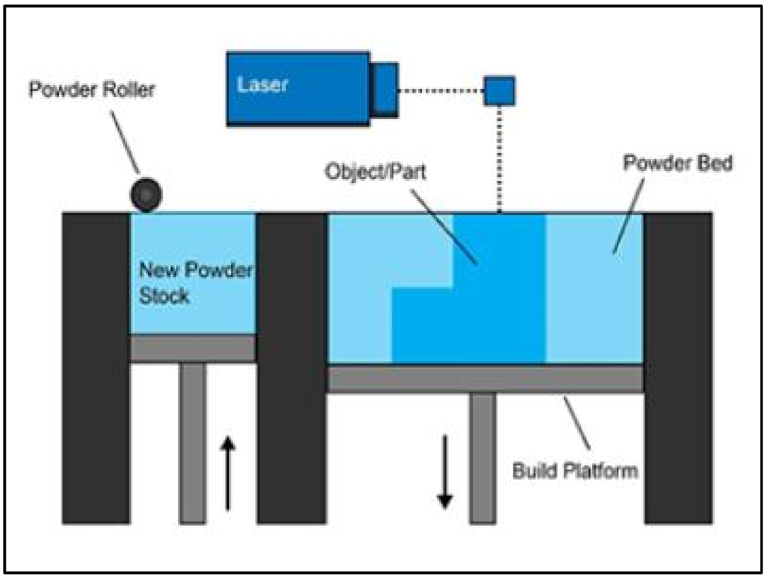

Figure 5. Power Bed Fusion process

The main advantages of the process are that it is relatively inexpensive, a large range of materials can be used (indeed, any powder based material, but in general common metals and polymers are the most used ones), it acts as an integrated support material, which reduced the waste of material and is suitable for visual models and prototypes.

In the other hand, the speed of the process is quite slow. Also, high power is required and the finishes of the pieces depend on the powder grain size.

3.1.6. Sheet Lamination

Sheet lamination processes include Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM). UAM uses sheets of metals, such as aluminium, copper, stainless steel and titanium, which are bound together using ultrasonic welding. The process repeats this steps building layer by layer the part. LOM uses a similar process but using paper and adhesive instead of metal and welding.

The process has the following steps:

1. The material is positioned on the cutting bed.
2. The material is bonded, over the previous layer, using the adhesive.
3. The required shape is then cut from the layer, by laser or knife. Step 3 can be also done before step 2.
4. The next layer is added.

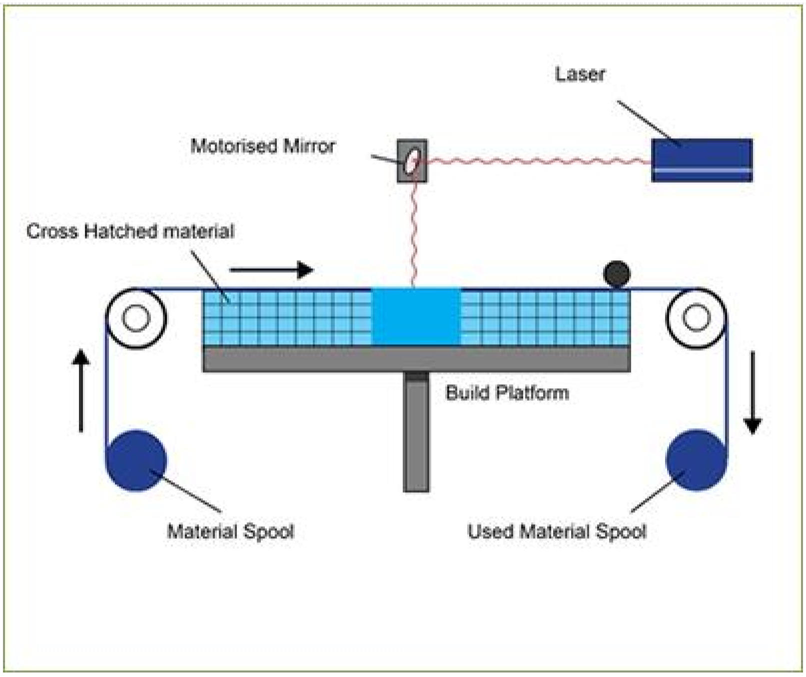

Figure 6.Sheet Lamination process

The process takes place at a low temperature and allows for internal geometries to be created and also, as the metal is not melted requires relatively little energy. In addition, the main feed material is paper which greatly reduces the cost. In the othe hand, laminated objects are often used for aesthetic and visual models and are not suitable for structural use and only a few range of material can be used.

3.1.7. Directed Energy Deposition

Directed Energy Deposition (DED) is the most complex process and it is usually used with metals but it can also be used with polymers or ceramics.

A DED machine consists on a nozzle mounted on a multi axis arm as shown in *Figure 7*. To know how does the process go, we are going to explain it step by step:

1. A multiple axis (generally 4 or 5) arm with a nozzle moves around a fixed object.
2. Material is deposited from the nozzle onto existing surfaces of the object.
3. Material is either provided in wire or powder form.
4. Material is melted using a laser, electron beam or plasma arc upon deposition.
5. Further material is added layer by layer and solidifies, creating or repairing new material features on the existing object.

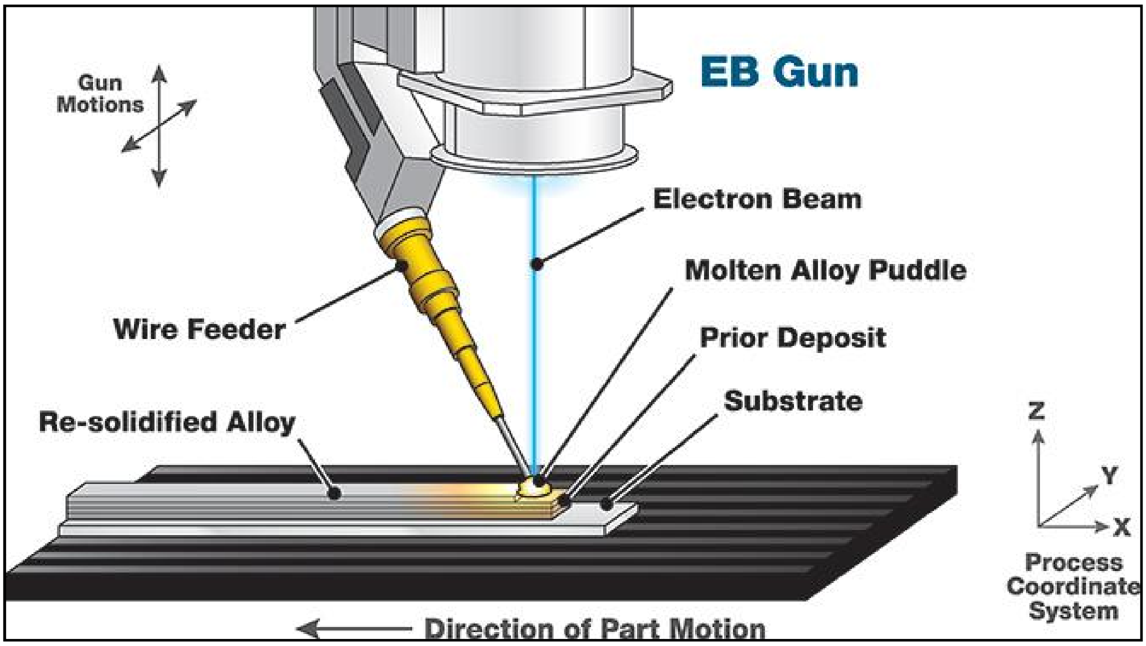

Figure 7. Directed Energy Deposition process

The main advantages of this process is the possibility to control the grain structure so it makes high quality pair work. In the other hand, post processing is usually required to achieve the desire finishes in the parts, the materials that can be used are very limited and it is a process that has to go further in investigation.

3.2. Extrusion existing technology

As mentioned in the previous section, the principle of Selective Deposition in additive manufacturing it mainly consists on building up a 3D model by adding melted plastic on a flat surface and mount it layer by layer. Of course, for building it up you first need to make a virtual design of it in your computer, aswell as having a 3D printer able to print the designed piece. 3D printers are gadgets or devices that can apply melted plastic in the three dimensions. They work in the following way: they start with a computer model of an object and then use it to control a robotic device. In the most common configuration, the head is moved by stepper motors or servomotors, but it is also possible that is the base surface has movement and the head stays motionless.

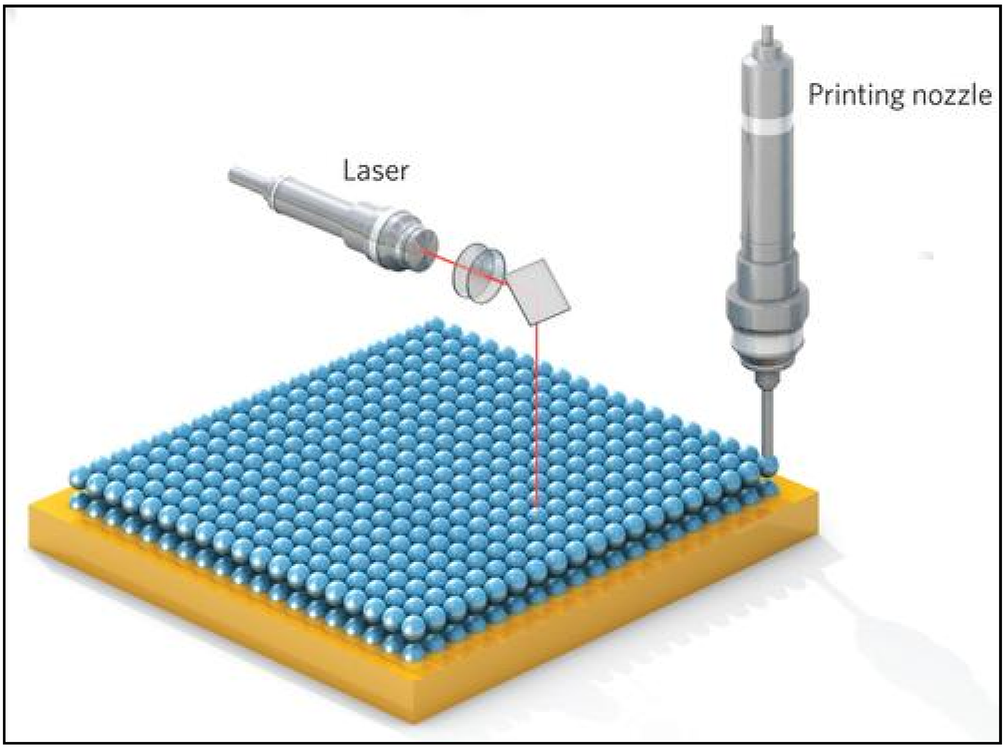

Figure 8. Additive Manufacturing process

In the past times we weren't able to reproduce virtual 3D objects into real ones, but now thanks to the additive manufacturing technology we are capable to print them up on a flat surface, adding melted plastic layer by layer creating our 3D output. This means that we can let down inkjet printers which can only print an image or a view of an object because we can now create our own object and print it in the way we want.

As we said in the previous section, we are going to focus in Selective Deposition techniques only, because the existing machine works with this procedure, but there are a lot of different ways to do the process of 3D printing. The key part on our project is the process of melting the plastic from the granulate so that it can be deposited on the platform and solidified after. Here we are going to describe the existing techniques for melting the plastic.

Extrusion based 3D printing processes make up objects through the deposition of material using a print head. In this case objects are produced by heating the thermoplastic material into a visco-elastic melt that is extruded and deposited layer by layer. There are three different methods to get the plastic melted:

a) The well-known FDM™-principle.
b) Syringe based extrusion.
c) The screw based extrusion.

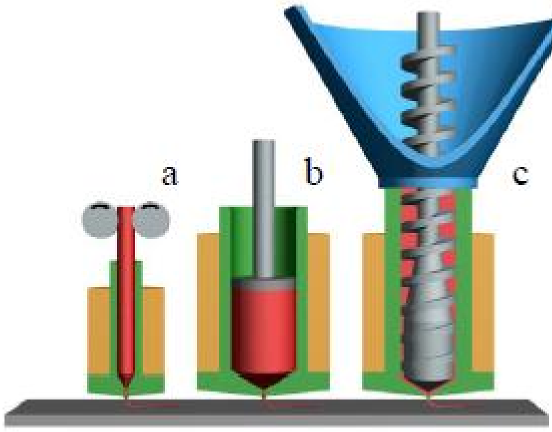

Figure 9. Extrusion based 3D printingmethods

3.2.1. Filament based 3D printing (FDM)

Fused Deposition Modeling (FDM) was developed by S. Scott Crump in the late 1980s and was commercialized in 1990 and is the most famous technique of the three Selective deposition techniques. FDM is an additive manufacturing technology commonly used for modeling, prototyping, and production applications.

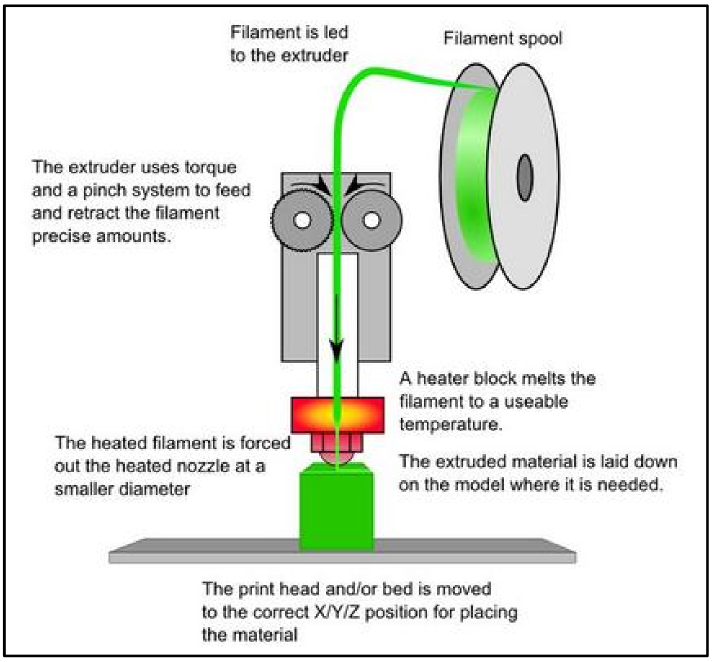

Figure 10. Filament extrusion 3d printing process

A plastic wire is forced to pass through the extruder. There it is heated and melted into a liquefied polymer then that melted plastic is forced to come out through the nozzle as the extruder keeps going. The incoming solid filament acts as a plunger to push and extrude the liquefied polymer through the nozzle. The plastic is deposited on the platform following the pattern to create the piece. Once a layer is processed, the head is raised or the building platform is lowered a layer thickness and a new layer can be deposited.

FDM systems are capable of producing parts from the largest range of thermoplastic materials, feature detail, surface finish, accuracy. FDM uses production-grade thermoplastics, such as acrylonitrile butadiene styrene (ABS), PPSF (Polyphenylsulfone), PC (Polycarbonate), and PC-ABS which improve mechanical properties of ABS. Because of the material properties, FDM parts typically withstand functional testing and have high heat resistance. Some companies have sterilized PPSF for medical applications. Some producers can deliver machines able to process polylactic acid (PLA) a biodegradable polymer.

Nevertheless, a big problem remains with this process which is the limited availability of commercial polymer fed materials. is therefore seen as a major shortcoming of the filament based 3D printing process.

That is one of the mains reason to develop a 3D printer capable of working with granulate plastic. Our project is focus on designing an extruder which works with PLA plastic granulate so we can overcome with the limit of material that can be used in 3D printing. After, it will be possible to work with all the different commercial polymer.

3.2.2. Syringe based 3D printing

Syringe based 3D printing is an extrusion process which overcomes the limitations of the filament based extrusion described in the previous point, especially in terms of the range of the materials that can be processed and because you can use the granular shape of the plastic which is the common shape for thermoplastics, and by extension the cheapest.

This configuration makes typically use of materials that solidify due to a chemical solidification. A deposit is filled with the material and heated to the processing temperature. A force is applied to the fed material by the displacement controlled plunger that pushes the material out of the deposit according to the generated path from the 3D model.

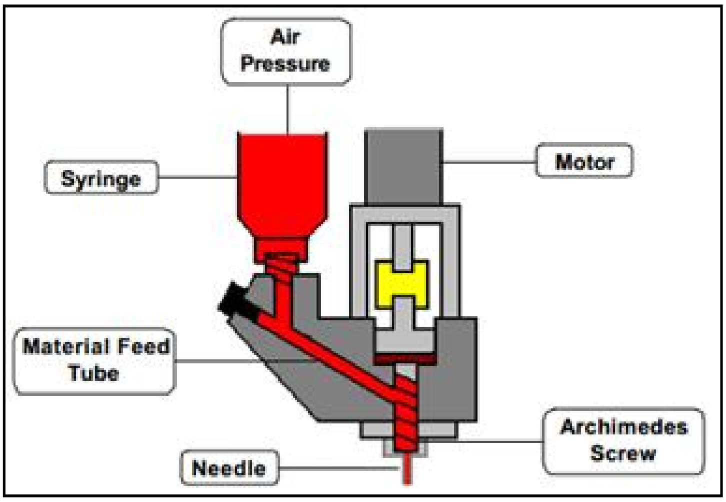

Figure 11. Syringe based 3D printing process

Despite of its simplicity and the advantages of the process, there are some important disadvantages also:

- If the object is too large, it can be necessary to refill repetitively the syringe causing interruptions in the building process and cooling down of the printed product and syringe, resulting in a poor adhesion between the layers.
- The material is heated all along the syringe so the higher material after a time at elevated temperature will suffer thermal degradation, resulting in poor material properties.
- It is possible that the syringe contains air which will interrupt the process and also air encapsulations in the material of the piece.

3.2.3. Screw based 3D printing

This last method could solve the mentioned problems of the FDM and the syringe process, especially the limited range of available materials. A three-section screw based extrusion process is the solution. It is commonly used in the plastic processing industry to create continuous profiles.

In this kind of extrusion, the feed material, which is the granulate plastic, is added into a hopper and melted thanks all along the three-section screw. The heat applied along the extruder and the pressure build up by the screw melt the polymer granules.

The main advantages of this way of extrusion are:

- Possibility of using commercial granules as fed material.
- Continuous process can be realized.
- The screw creates and homogenous melting and the material suffers less degradation.
- Lots of different polymer can be used as polypropylene (PP), polyethylene (PE), polystyrene (PS), polylactic (PLA), polycaprolactone (PCL), …

As we have said before the main object of the project is to design this kind of screw based head for a 3D printer. The reason this technique is not commonly used is because of the complex design of the three-section screw. However, this type of screw is required to prevent interruption of the extrusion avoiding trapped air in the melt.

3.3. The extrusion process

The extrusion is a process used to create objects with defined cross section. Extrusion involves passing under the action of pressure a material through an orifice with fixed form in such a way that the material acquires an equal section as the orifice. Extrusion may be continuous or semicontinuous and also the process may be done with heated or cold material.

Plastic extrusion typically used plastic granulate or pellets that are usually dry in a feed tank or hopper before going to the feed screw. Polymer resin is heated to melt by resistance found in the barrel of the extruder and the heat from friction screw extruder.The screw forces the resin to pass through the head into the desired shape and then the plastic is cooled and solidified. In some cases, after the extrusion, the material is passed through a long die in a process called pultrusion.

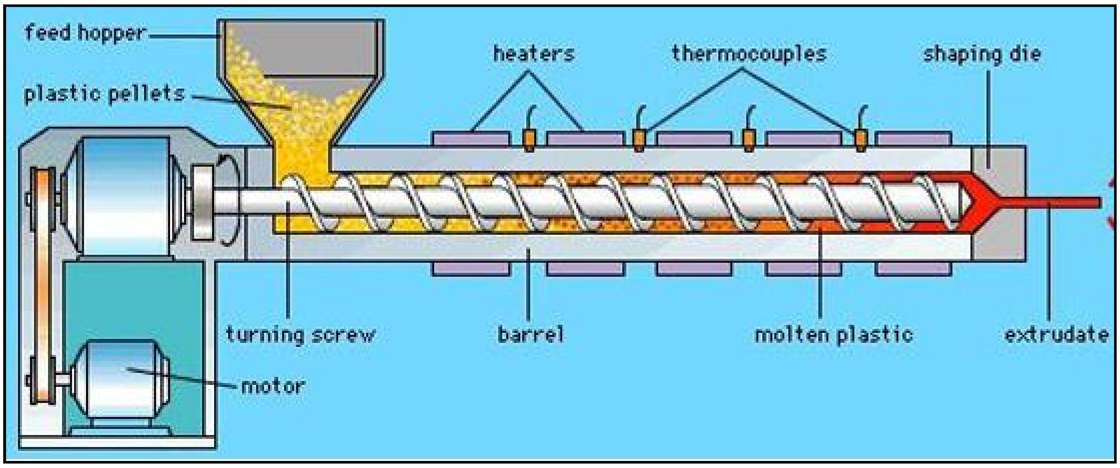

Figure 12. The extrusion process

Extrusion has high productivity and is the most important process of obtaining plastic forms. Its running is the simplest, because once the operating conditions are established the production continues without problems as long as there is no greater disturbance. In addition, the cost of extrusion machinery is moderate compared to other processes such as injection, blow molding or calendering, and with good flexibility for product changes without making major investments.

The general classification of the different types of polymer extrusion techniques are:

- Single screw extruders:
  - Conventional extruders
  - Co-mixers extruders
  - Venting extruders or degasification

- Without screw extruders
  - Pumps
  - Disc extruders

- Multi-screw extruders
  - Twin screw extruders
  - Intermeshing screws
  - Not intermesh Screws

- Extruders with more than the screws
  - Planetary roller
  - 4screw extruders

We are going to focus on the single screw extruder which is what we are trying to design for our 3D printing.

3.3.1. Single screw based extrusion

All the types of extrusion have similar characteristics and elements. So, we are going to explain an equipment description of a single screw extrusion, as it is the kind of extrusion that we will use during the project, in order to learn its main functions and describe where are we going to find the main problems while designing.

Basically, an extruder consists on a central metal shaft with helical blades called spindle or screw installed inside a metal cylinder coated with an electrical heating jacket. At one end of the cylinder there is a hole where a feed hopper is installed, generally with conical shape, for the raw material. At that end is also allocated the spindle drive system, compound of a motor and a speed reduction system. At the other end of the screw, the material outlet is located and so the die which defines the final form of the plastic.

To give a better knowledge of who does the extruder work, we are going to describe the main elements in which it is divided and a brief explanation of all of them.

- **Hopper cylinder:**

The hopper is the tank where the pellets of plastic material are placed for feeding the extruder. It should have the right dimensions to be fully functional. If the design is not correct, mainly in the angles of descent of material, it way could have deadlocks in material and the extrusion will be forced to stop.

Sometimes a hopper with vibrating system can solve the problem and avoid the deadlocks. It is also possible to use a hopper with a screw inside to achieve the feeding. It is also importan to know that there are some type of hoppers, the drying hoppers, which are used to remove the moisture from the material.

- **The feed throat:**

It is the feed opening through which the plastic material is introduced to th extruder. It is usually necessary to cool down the feed throat to keep the plastic partticles from sticking to the wall.

- **Cylinder:**

It is a metal cylinder that houses the spindle and constitutes the main body of the extruder. It forms, with the screw, the melting chamber and the pumping of the extruder.

It must have a compatibility and resistance to the material which is going to process. For this reason, different methods of surface hardening are applied to the inner walls, which are those that are exposed to the effects of abrasion and corrosion during the process, in order to minimize any wear.

The cylinder has electrical resistors that provide the heat energy required to melt the material. For the best conservation along the cylinder and prevent changes in production quality by variations in the temperature, it is usually used a material with low thermal conductivity, such as glass fiber or filter, to isolate the body of the cylinder.

Although it may look contradictory, each heating zone of the extruder screw is accompanied in most commercial equipment, by a fan which allows the temperature control by airflow over the surface required. The extrusion temperature can only be controlled precisely by the combined action of the electrical heating bands and fans for each zone.

Therefore, the key points in the design of the cylinder are that it has:

- Maximun durability.

- High heat transfer.

- Minimum dimensional change with temperature.

To facilitate processing materials with low friction coefficient sometimes s necessary to use an extrusion cylinder which has channels, with specific forms, on its inner surface. To be carried forward, the material should not rotate together with the screw, or at least must rotate at a lower speed than the screw. The drag force is the only force that prevent the material turns with the screw. The higher friction the lower rotation of the material with the screw and, therefore, more forward movement.

Grooved fee zones help to control the coefficient of friction polymer-cylinder by geometry reducing the sensitivity to temperature and the thermodynamic properties of the resins. Moreover, grooved feed zones allow to increase the volume of the feed section, accelerating the merger and thereby they achieve increases in the extrusion rate.

- **Barrel Heating and Cooling:**

Heating is usually done with electrical band heater along the length of the extruder. It is necessary to help the screw to melt the plastic.

Sometimes is also necessary to cool the barrel if the internal heat generation rise the barrel temperature above the setpoint. This is likely to occur with high viscosity plastics and high screw speeds. Cooling is usually done with air but water can be used as well.

- **Spindle or screw:**

It is the most complicated piece to design and the most important because it largely determines the quality of the extrusion process. Its function is to melt and transport the plastic. It performs three basic functions: solid conveying function, melting function and metering function or pumping function. The three screw functions occur simultaneously over most of the screw length and they are strongly interdependent. In every screw there are three different zones, which are: the feeding section, the compression section and the metering section.

The screw extruder has one or two spiral "wires" of constant width along its axis to form a helical channel. The measured diameter to the outside of the yarn is the same throughout the length. However, in general, the channel depth decreases from the feed end to the end of the dice.

The dimensions for the screw usually follow a L/D ratio between 24:1 and 32:1, but there are also special applications where extruders are built as short as 10:1 L/D and as long as 50:1. The proper dimensions are determined by the process and applications that the screw is going to be used in.

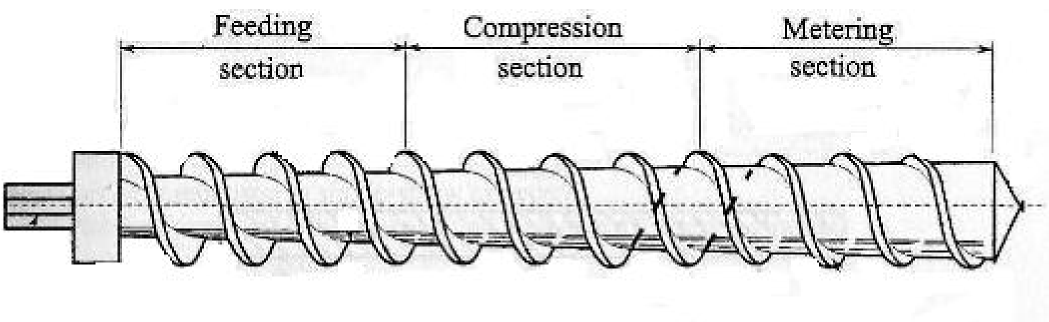

Figure 13. Parts of the screw.

- **Breaker plate:**

Breaker plates are a thick metal puck with many holes drilled through it, which acts as a screens filtering contaminates from the final product. The breaker plate also serves to create back pressure in the barrel. Back pressure is required for uniform melting and proper mixing of the polymer.

It also does the function of converting "rotational memory" of the molten plastic into longitudinal flow.

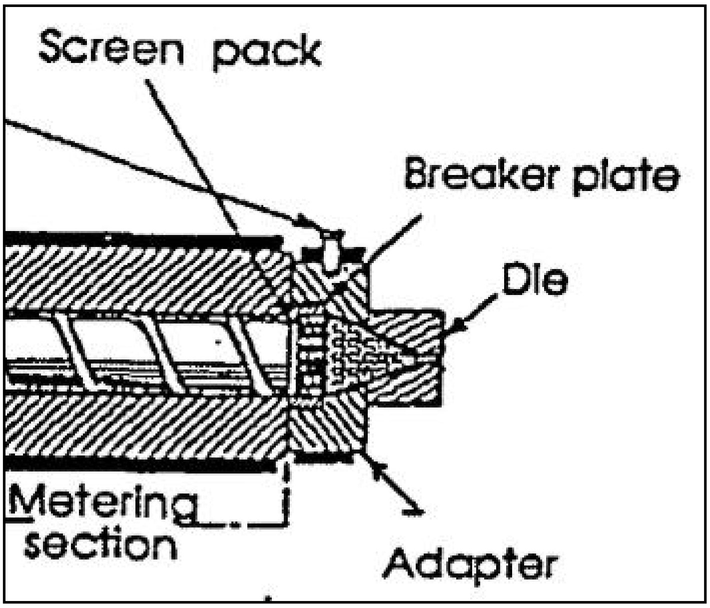

Figure 14. Breaker plate and die situation in the extruder.

- **Nozzle or die:**

After passing through the breaker plate the melted plastics enters the die. The die is the part responsible for giving the final shape to the plastic. The flow channel in the die should be designed in such a way that the plastic melt achieves a uniform velocity across the die exit. The shape of the land region, which is the end of the die, corresponds to the shape of the extruded product.

However, the size of the final product is not exactly the same as the land region. Because of the several variables affecting the size and the shape of the final product, such as the drawn down, cooling, swelling or relaxation, it is difficult to predict the how the die should be designed.

Nowadays die design is still based on experience and on trial and error process rather than on engineering calculations.

3.4. Printing material: PLA

Although there are many possibilities of materials that can be used in 3D printing, such as Acrylonitrile Butadiene Styrene (ABS), High Impact Polystyrene (HIPS), Polyethylene Terephthalate (PET), Laywoo-d3, Ninjaflex, nylon,... , we are going to focus our project in the material that the existing machine uses, that is indeed the same material that we are going to use in the redesigned machine: the polylactic acid (PLA).

3.4.1. Introduction

The polylactic acid, commonly named as PLA, is a biodegradable thermoplastic polyester of low molecular weight, that comes from renewable resources. It was discovered by the scientist Wallace Carothers in 1932 while working for Dupont companies. It is one of the plastics more researched and developed due to its multiples applications on the market. Nowadays it is the most used plastic for 3D printing.

This interesting polymer originated in starch from plants such as corn, cassava, wheat, beets or sugar cane, which facilitates extraction source away from the transformation processes of hydrocarbons characterizing obtaining other polymers. It was included in the list of plastics FDA (Food and Drug Administration) for its applications in the field of biomedicine and food.In 2010 it has the second highest comsuption volume of any bioplastic in the world.

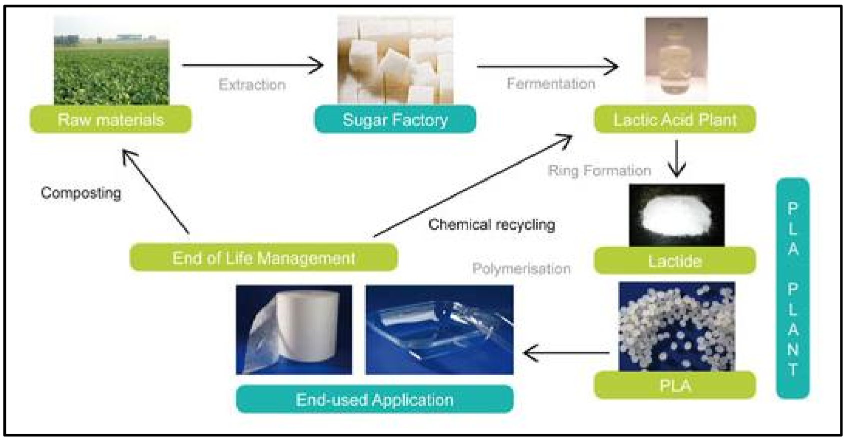

Figure 15. PLA cycle of life.

3.4.2. Properties

To show up the properties and advantages of PLA we are going to compare it with ABS (Acrylomitrile butadiene styrene) which is also one of the most used materials for 3D printing. ABS is a tough hard plastic, which allows to be sanded polished, drilled, etc. These features make it ideal for printing mechanical parts or pieces that need to be handled or machined after printing.

1. PLA has a density between 1.2 and 1.4 g / cm^3, making it heavier than ABS material.
2. Shore hardness (scale measures hardness of plastics) is 63.5 degree, being higher than ABS. What makes it a harder plastic than the previous one.
3. It is more rigid than the ABS, having a modulus of elasticity 3.63 GPa, making it difficult to deformation under load and makes it a less elastic material.
4. Less impact resistance than ABS. It has mechanical properties similar to PET.
5. PLA melting temperature: 173-178 ° C.
6. PLA Glass transition temperature: 60-65 ° C.
7. PLA extrusion temperature between 180 and 220 ° C.
8. PLA printing temperature between 190 and 210 ° C.
9. Good adhesion to a large variety of surfaces.
10. Insoluble in water.

3.4.3. Applications

PLA is processed by extrusion in 3D printing, injection molding, film and sheet casting, providing access to a wide range of materials.

PLA is used as a feedstock material in 3D printers in additive technology process to conform prototypes as well as final products.

Because it is able to degrade into innocuous lactic acid, it is used for medical purpose. Nowadays it has more and more applications as medical implants in the form of anchors, screws, plates, pins, rods and as a mesh.

In addition, PLA is also used in packaging, which is by far its main function, as it is biodegradable. It is useful for producing loose-fill packaging, compost bags, food packaging and disposable tableware.

3.4.4. PLA printing

As feed material for 3D printing PLA is used to create functional products as we said with medical purpose and for packaging food.

When printing PLA, we can see that is easier to print it than others. We can print with a temperature between 190 and 210 ° C. For the configuration of the printer base plate there are several options:

- **Cold printing**

One of the options when printing this material is to use a configuration without adding temperature in the printer base plate. This causes the printer consumes less electrical power and do not have to be heated the surface on which the workpiece is supported.

In this configuration a fixer which adheres the part to the base is needed and also, ensure thorough calibration as fixing the first layer to the base printing is critical.

However, the possibility of printing cold with this material, is dismissed when you want to print pieces of long prints, large geometries and medium-high speeds. It is likely that areas of the workpiece can completely come off the base along printing.

- **Hot printing**

The most commonly option used by 3D printing users who consume this type of material is to use a heated base. Placing the base temperature higher than PLA´s glass transition temperature.

It has to ensure that tensions near the printer base are minimal, because, with low tensions the piece could came off or warp. Despite we need to heat the base, we can not set a temperature much higher than the glass transition temperature, since they could give different creep phenomena in the material (as it would be too soft). Various printing defects may also appear on the walls and face fixed to the base.

In order to avoid these problems a fixer can be used to ensure a good adhesion of the part to the base plate.

3.5. Description of the existing machine

The existing machine has a cartesian axis movement. The x and y axis movements are given by the head and all its components and the plate is moved in the z direction. The plate is holded by 4 axes, one in each corner, all of them connected by a transmission band which is moved by a motor, as it is shown in *Figure 16*. Its track total measure is 510 mm.

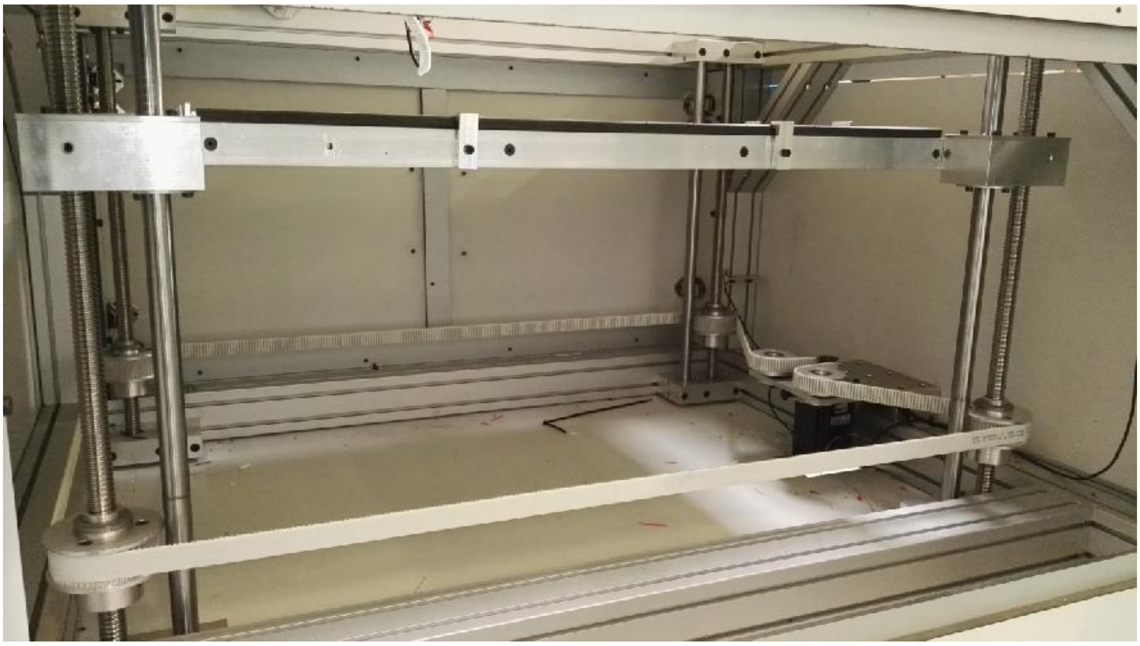

Figure 16. Movement system in Z direction of the existing machine.

The extruder, the head and the rest of the components are placed in the x axis, which is moved by a motor also. At the same time, the x axis is set in two y axis, which each of them are also shifted by a motor with the same characteristics as the one located in the x axis. It has a track of 800 mm for the x axis and 990 mm for the y axis.

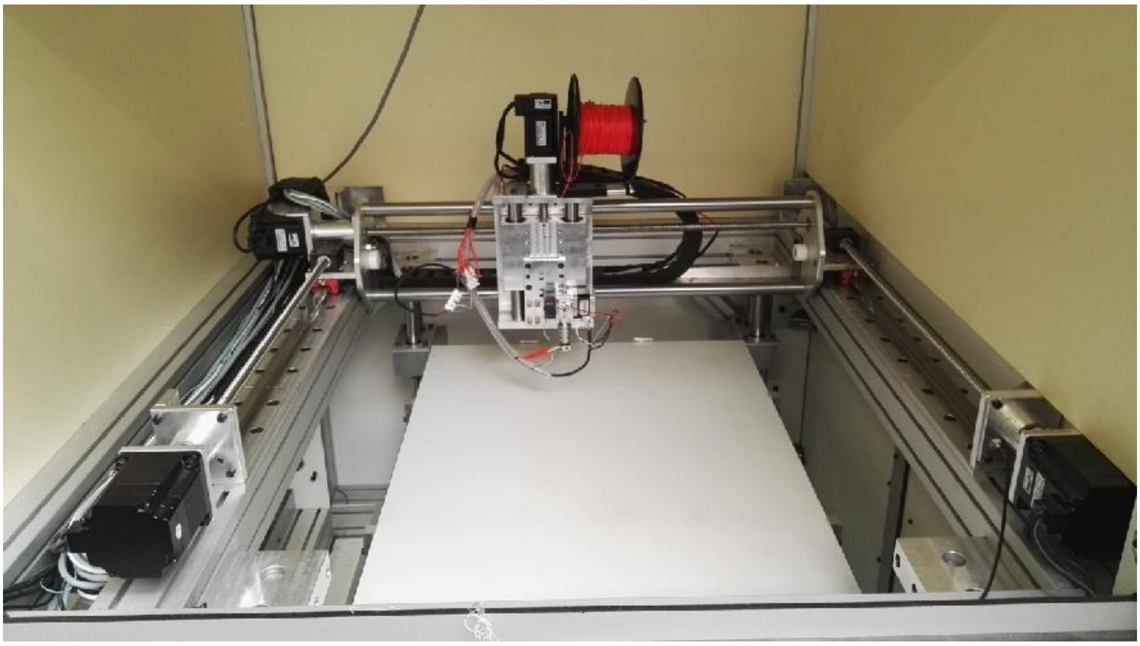

Figure 17. General view of the existing machine.

The plate has a rectangular shape and its dimensions are 660x915 mm. So the printing area's size available is 603900 mm2. The head, in which we will placed our extruder, has a dimensions of 175x110x245 mm.

All this elements are going to be maintained when designing the new machine, but what changes in the redesign in the head of Figure 18. A new one is going to be attached in the vertical plate that already exist. As the existing machine is prepared for printing the PLA plastic in a filament shape we have to change this part; the other elements don't influence in the shape of the material.

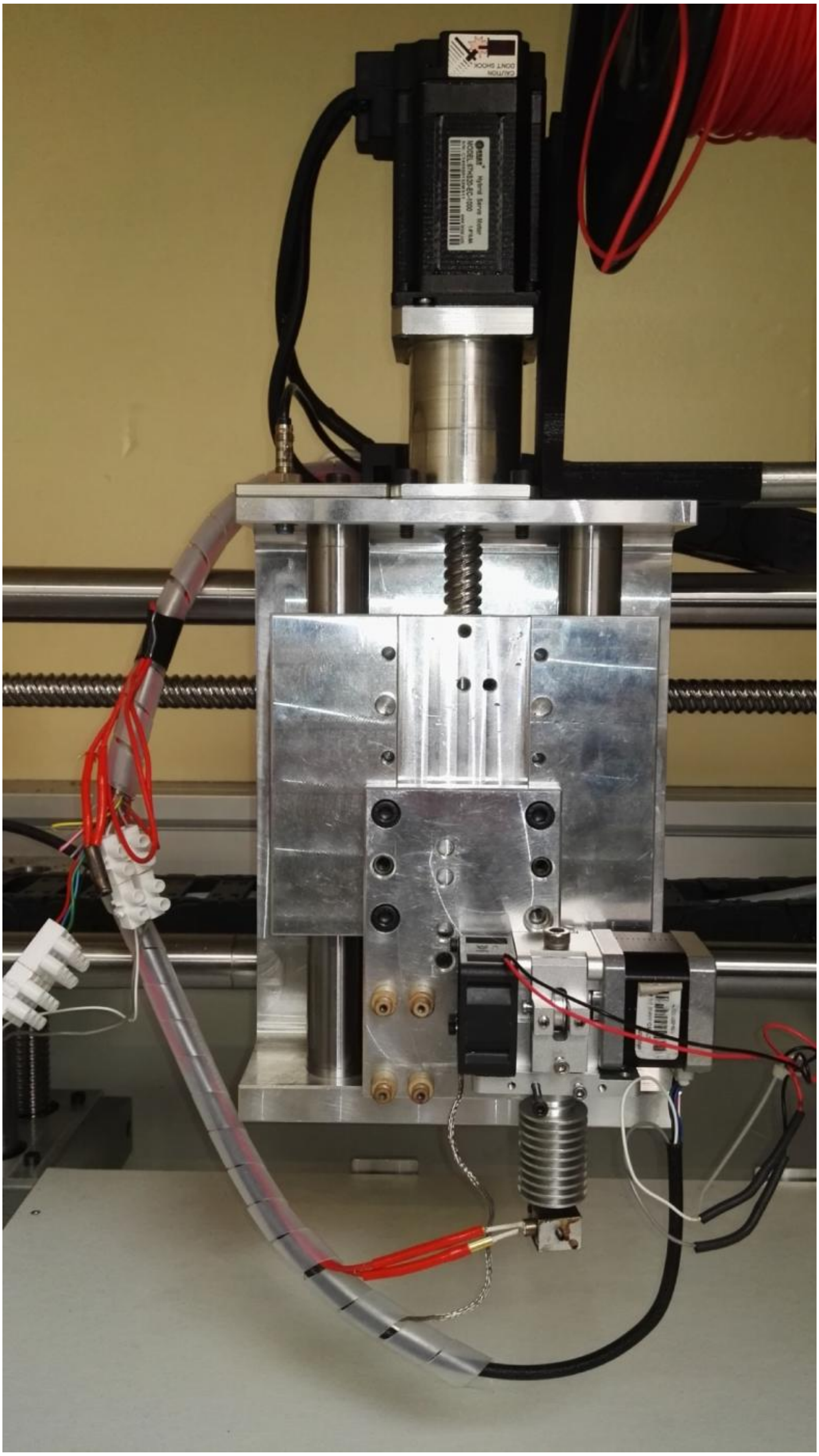

Figure 18: Head of the existing 3D printer.

4. Options of redesign

First of all we are going to explain which parts will be changed in the new design. As we want to take advantage of the existing machine, we are thinking in just designing a new head with all its components and attach it to the existing plate where the actual head is placed. If this case is possible, we will only have to design the system to start with the material as powder instead than as filament.

In this section we are going to explain the different option we have thought about for the redesigned printer head, and the advantages and disadvantages for each one.

4.1. Option 1

Aparently this option is the simplest one but there are some problems to be solved. The biggest problem is when the 3D printing stops working and all the plastic inside the canal lowers its temperature and becomes solid. As there aren't heaters throughout the canal, the material gets stuck into its walls and the printing process couldn't be restarted.

The process starts feeding the hopper with the plastic. The material passes through the screw while been extruded and when it comes out of the cylinder as melted plastic, it goes inside the canal until the head to be deposited into the base plate.

In this option, not only the movement of the head is keep, but also the nozzle and the plastic canal that guides the material. In this way, the only part to be redesigned would be to include an extrusion process that melts the material to transform it into filament. It would be easy because as long as we achieve the plastic in its filament shape the process would be exactly the same as the existing one.

As it was said before, the initial process is easy to be set but the most difficult part to be solved is to restart the printing without the problem that the material gets stuck.

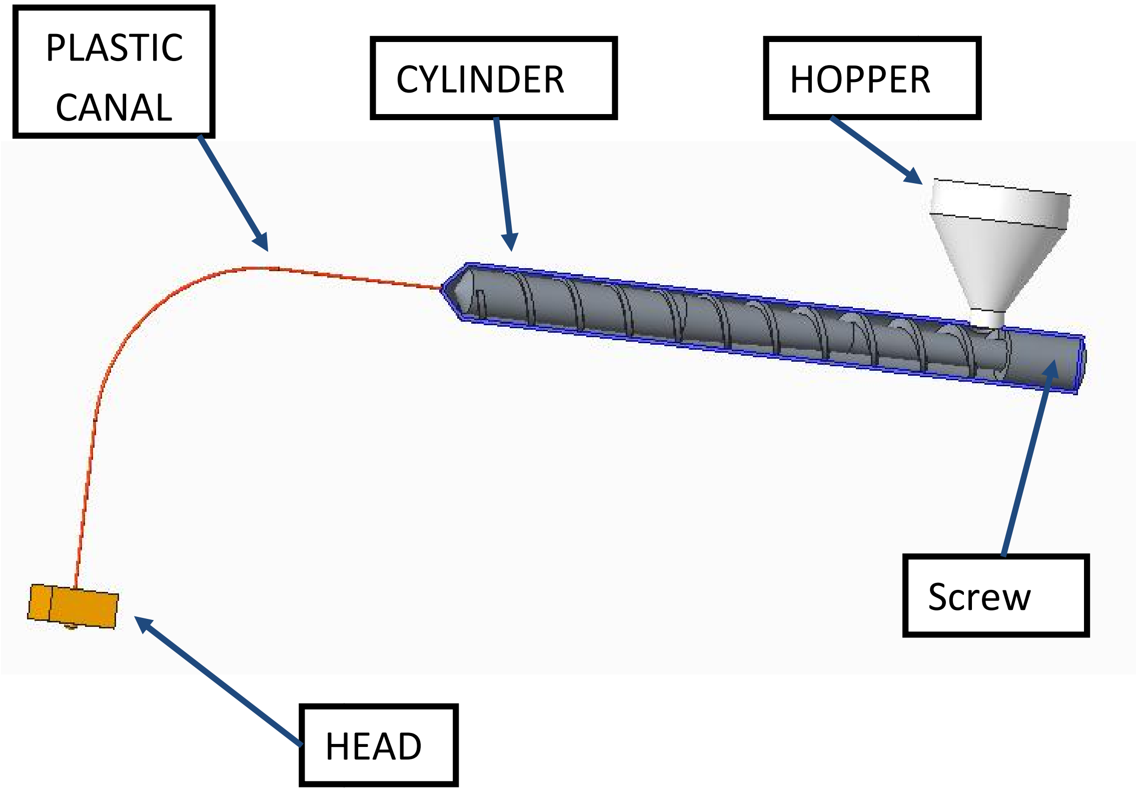

Figure 19. Overview of Option 1.

- **Advantages:**

- The printer's head is already made.

- The moving system is kept from the existing machine.

- Easiest design.

- **Problems/disadvantages:**

- When the printing process is stopped, the plastic in the tube that connects the extruder to the head is solidify. This makes impossible to start another impression.

- As the PLA comes out at a very high temperature of the extruder, it could stay stuck in the tube walls.

Conclusion: we dismiss this option because the problems that could appear are difficult to be solved. This option would be the easiest one to implement it for the first time but then, when stopping printing, the material would get stuck and it wouldn't restart with the process.

4.2. Option 2

The particularity of this option is that the cylinder and all its components are fixed. The base has the triaxial movement so the system attach to it is more complex to design. In addition, two different screws (an horizontal one and a vertical one) have to be designed, but in the other hand the head is not needed.

The process starts feeding the hopper with the plastic. The horizontal screw drags and breaks the granulates until the material reaches the vertical screw. In this screw, the extrusion process continues until the material comes out of the nozzle and it gets deposited in the motion base.

The motion plate has the inconvenient that we don't have a reference to be based on. The existing 3D printing has its movement in the head and the rest of the components and the plate could be very heavy to be moved. It can be designed, but it is more complex than the other options. It is actually the only redesign in which varies the 3D printer movement system.

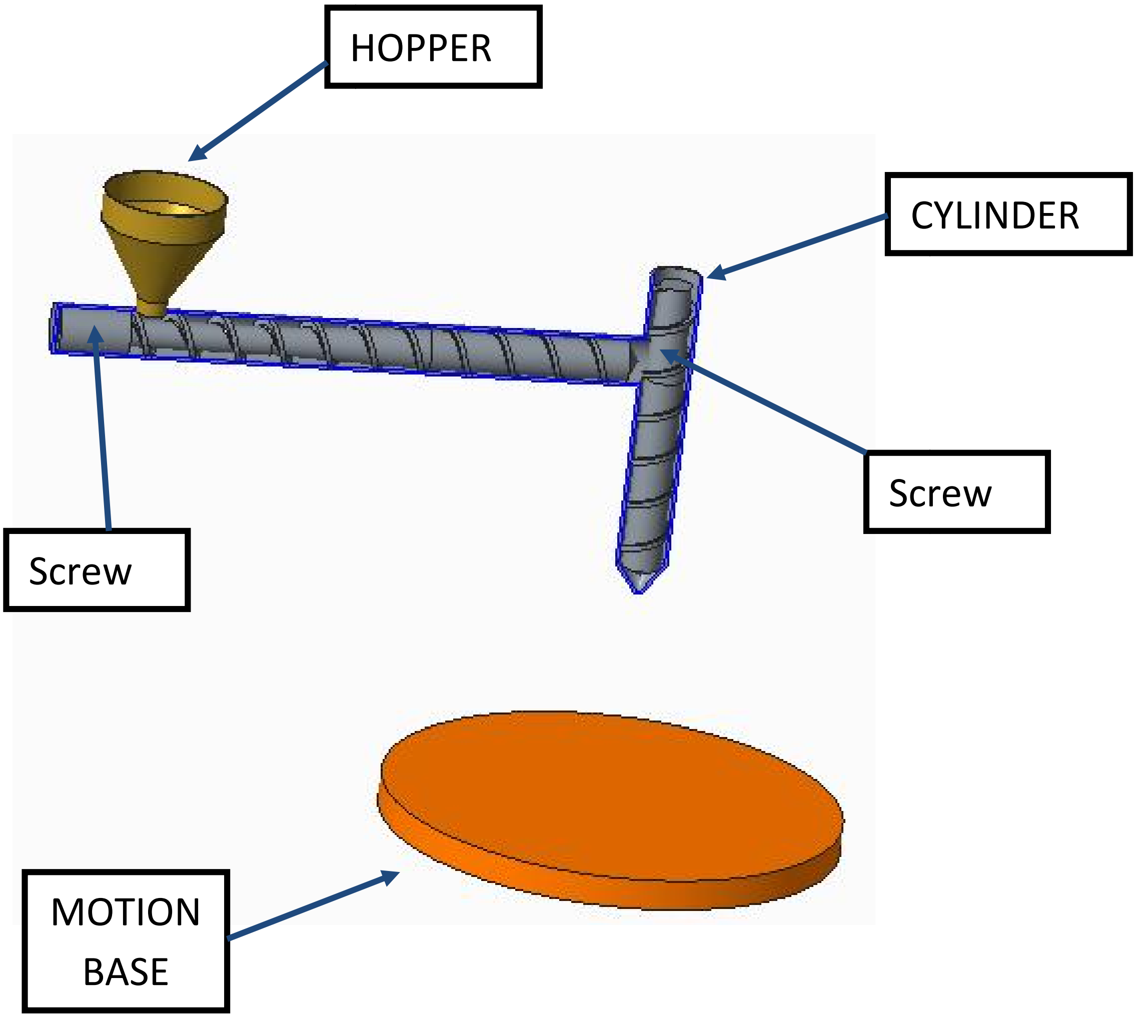

Figure 20. Overview of Option 2.

- **Advantages:**

- It allows a larger extruder and it avoids the limitation in weight and size.

- It avoids the problem of the granulate's size.

- Cable is not necessary.

- **Problems/disadvantages:**

- A new and complex movement system has to be designed.

- The plate could be very heavy to be moved.

- Two extruders will be needed and for this reason the cylinder has to be more complex, as it has to contain both of them inside.

Conclusion: we dismiss this option because it is difficult to design a new movement system for the 3D printer. As mention before, we would like to take advantage of as many parts that are already designed and with this option we don't keep the movement as in the existing machine. Although the fact that a head isn't needed makes avoiding a lot of problems with the temperature, the movement system is too much complex to be designed.

4.3. Option 3

This option considers the possibility of melting pellet by pellet one after each other. Due to the small flow rate of plastic needed it may be possible to create a device, which introduces pellet by pellet in the cylinder. Then the heater would melt the pellets one by one. Of course, it has to be calculated how much temperature is needed to melt them.

The nozzle and the hot end would be the same as the common filament 3D printers. However, the energy used in the heater would be lower because it has to melt less material.

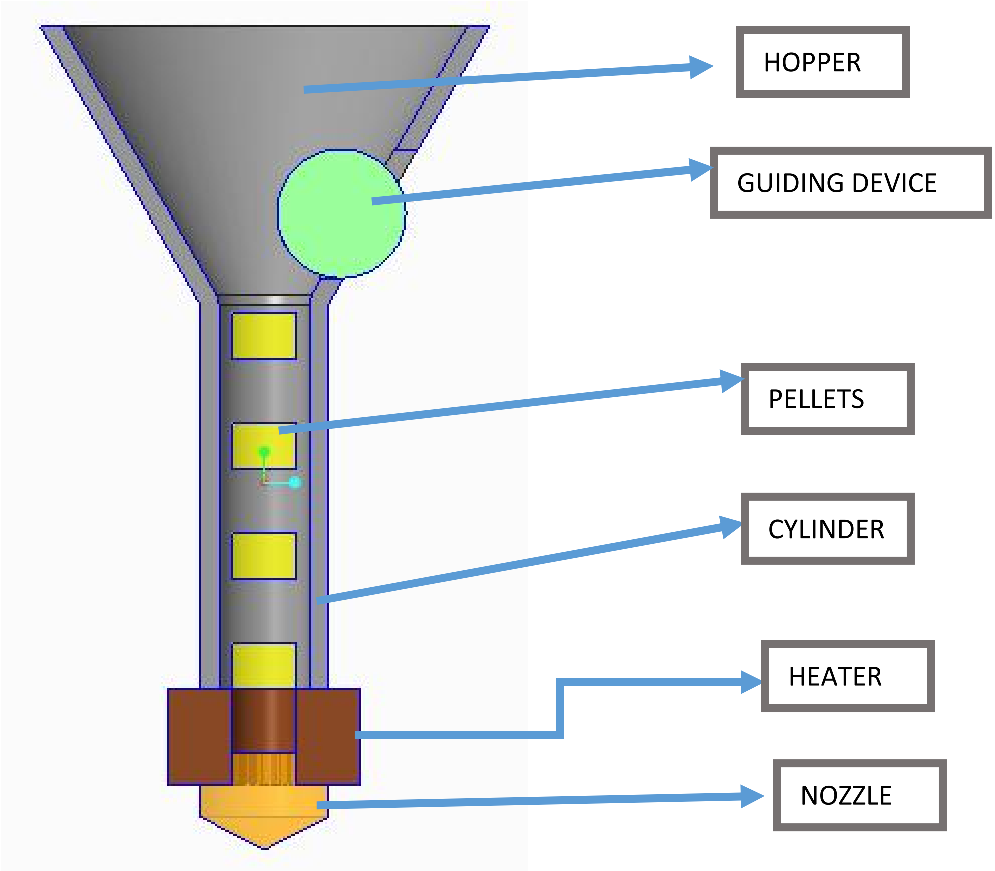

Figure 21. Overview of Option 3.

The main issue of this option is that despite it is easy to melt the pellet, the melted plastic won't drop by itself. The 0.4 mm end of the nozzle makes it necessary to apply pressure to make the plastic come out of the extruder and this is not easy.

One option to solve the problem is to add vacuums at the end to vacuum out the plastic once is melted. The design of this head is probably the most difficult one because there is nothing similar so there are no examples. In addition, the design of the guiding device is also inventing a new part with no example to base on. Basically this design should be made through try and failure, making experiments to collect experimental data.

- **Advantages:**

- It avoids designing and creating the extruder.

- Low energy is used because is easy to melt one pellet.

- Small size and low weight.

- **Problems/disadvantages:**

- It is difficult to achieve a continuous flow.

- Pressure will be needed over the plastic, otherwise the melted plastic won't come out through the nozzle.

- A device that divides the pellets one by one has to be designed.

- Based in experimental data.

Conclusion: we dismiss this option for our head, as it is no possible to come up with a functional design with the means available to us. Also because we consider it as an inefficient method as it has to be designed to work pellet by pellet and not with a continuos mass of material.

4.4. Option 4

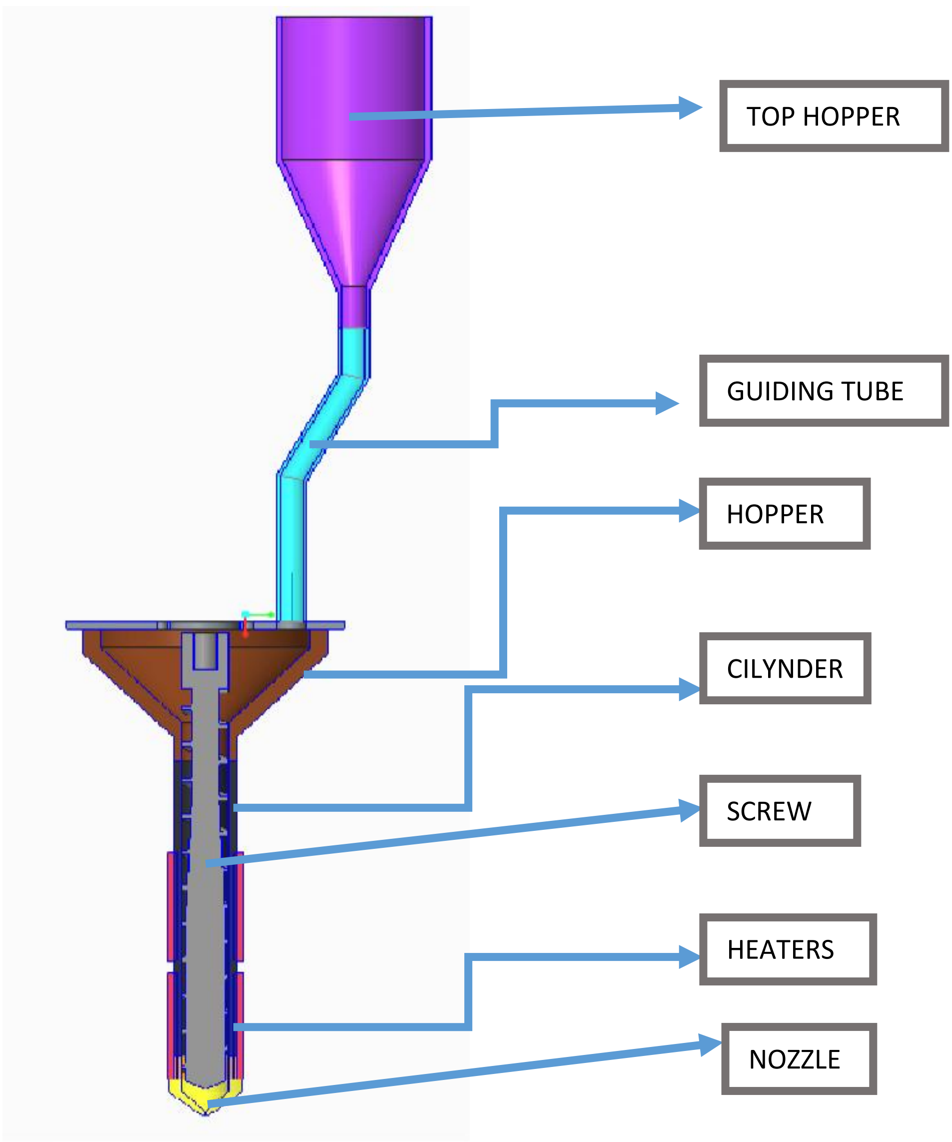

Figure 22. Overview of Option 4.

The last option that we have consider is to design a small extruder which would form the main part of the head of the 3D printer. This extruder should be feed with the plastic through a hopper placed on the top of the machine.The head should move over the base plate in three space directions to be able to create the 3D parts.

This option allows a continuous process due to the top hopper which is fixed on the top of the machine and can be refill at any moment, even when the printer is printing. From the top of the machine the granulates will be guide through a tube to the extruder. Then the screw would force the plastic granulates to enter in the cylinder. Thanks to the heaters on the cylinder and the friction the extruder will melt the plastic generating the liquid plastic that will drop to create the parts. The screw itself will act as the pump, due to the high pressure generated in the interior of the cylinder.

This provision for the printer head allows the machine to use plastic granulate as feeding material, instead of the commonly used wire, which will allow to print a large range of materials that cannot be printed nowadays. The extruder will melt the granulates and creates the plastic flow needed to print. In addition, the way it would be feed allows a continuous feed to the hopper of the extruder even when the head is moving.

Having a screw extruder gives the possibilities to regulate all the process of extrusion, which means that we can control the speed of the screw and the temperature of extrusion. Also this extruder heads allows different temperatures for the extrusion, as the heaters can be regulated.

- **Advantages:**

- Print in a continuous process.

- Print large range of plastic, due to the use of granulate.

- Avoiding the wire, it can print with any mix we want to do at any moment.

- **Problems/disadvantages:**

- The dimensions of the head have to be very small; otherwise the printer's head would be very heavy to be moved.

- As a result of the extruder's size, the granulate's diameter has to be very small before entering to it.

- Expensive to fabricate the small pieces.

Conclusion: as it is the option with less difficulties to be solved and it has all the characteristics needed, we are going to choose this option as t redesign the existing 3D printing machine. In the following sections this option will be extended with all the parameters and calculations.

5. Design parameters

5.1. Screw parameters

This point will clarify the calculations we made to decide the screw parameters. This is the most important part to design the 3D printer as the screw has to have specific measures to be able to break and drag the plastic material till the nozzle.

The screw has to be very small in order not to be very heavy to make the printing movements. In general we are very limited for this reason so the first step is to decide the measures of the screw that will delimite how much is going to occupy the screw in terms of volume and, by extension, mass.

5.1.1. Screw Threaded part

The diameter we decide to work with is 15 mm and for the relation between the lenght and the diameter we choose, 10/1. The reasons to take the measures and not any others are based basically on the fact that the screw has to be the smallest size possible without increasing very much the price. So we consider 15 mm to be the smallest diameter with reasonable price and with precise usefulness. In addition we choose 10/1 for the relation L/D because we consider 150 mm the maximum lenght keeping a light screw in terms of weight, taking into account that if the relation L/D is bigger, the price will be lower.

There are many parameters that can be calculated with its relation with the diameter. Most of the screws have these proportionality between these parts, so it is the cheapest way to design it, as for example choosing the same size for the pitch and the diameter or calculating the channel depth and width with a general relation with the diameter.

Diameter: D = 15 mm

Lenght: L = 150 mm

Pitch: t = D = 15 mm

Helix angle: $\varphi = \tan^{-1}\frac{t}{\pi \cdot D} = \tan^{-1}\frac{15}{\pi \cdot 15} = 17{,}65º$

Number of channels: m = 1

Initial channel depth: $h_1 = 0{,}2 * D$ = 3 mm

Ridge width: $e = 0{,}12 * D$ = 1,8 mm

Filet clearance: δ = 0,002 $* D$ = 0,03 mm

Compression relation : Z = 3

Final channel depth: $h_2 = h_1$ / Z = 3 / 3 = 1 mm

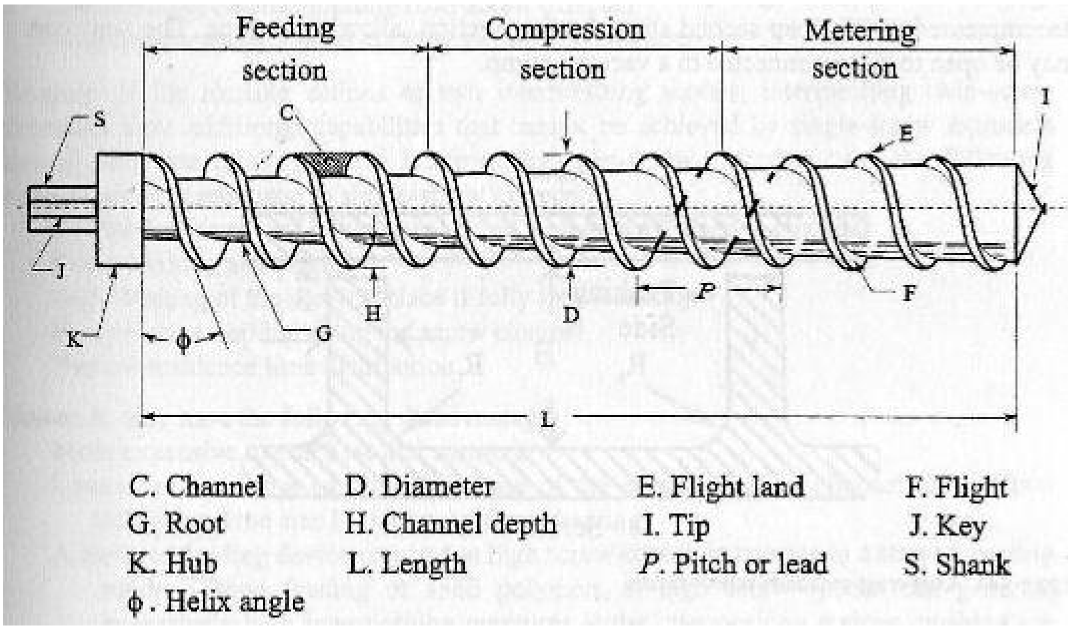

Figure 23. Screw parameters and nomenclature.

We based our decission of the zones' lenghts on the percentage from the total lenght that normally has each zone. For the feeding zone is between 20% and 25% of the screw lenght, for the compression zone between 32% and 38% and for the metering zone between 40% and 45%. We decide three exact lenghts inside this percentages:

Feeding zone lenght: L_1 = 33 mm

Compression zone lenght: L_2 = 52 mm

Metering zone lenght: L_3 = 65 mm

We can easily delimit the radius for each part by substracting to the general diameter, the channel's depth of each zone:

Feeding zone root radius: r = $\frac{D}{2} - h_1 = \frac{15}{2} - 3$ = 4,5 mm

Metering zone root radius: R = $\frac{D}{2} - h_2 = \frac{15}{2} - 1$ = 6,5 mm

5.1.2. Screw unthreaded part.

We decide the dimensions for this part in order to be able to join the motor to the screw and to adapt the measures for proper operation of the 3D printer (as they have to be as small as possible).

The exterior diameter has to be the same one as the screw diameter: Dext = 15 mm. With the same reasoning the hole has to have the same dimensions as the part of the motor attached to the screw: an interior diameter of 8 mm and a depth of 15 mm. Finally we choose 25 mm to be the total lenght of this part, so it doesn't add a lot of weight but it stills having enough size to be attached to the motor.

5.1.3. Screw weight

Now that we have decided and calculated all the measures for the screw we are going to calculate the volume of the screw as accurate as possible and then with the material's density we will be able to obtain the total weight that the screw has. With this point we will prove that the screw size fits for our 3D printing and it is not too heavy to dismiss this design.

To be precise we have to divide the screw in parts: the three zones (feeding, compression and metering), divided by root and filets each of them and the unthreaded part of the screw. We consider the peak negligible comparing with this parts so it wont be calculated.

The number of turns of the filet for each zone comes from dividing the total number of turns between the percentage that each zone has in terms of lenght. So for our dimensions (L = 150 mm) and pitch (t = 15 mm) we have 10 turns. The turns in each zone are: 2,2 for the feeding zone, 3,4 for the compression zone and 4,4 for the metering zone.

Now we just need the filet lenght to be able to calculate the volume of the whole screw. It is geometrically related with the diameter and the pitch, so it can be calculated as:

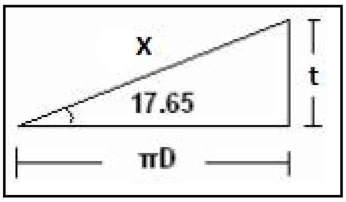

Figure 24. Filet geometry.

$$X = \sqrt{(\pi * D)^2 + t^2} = \sqrt{(\pi * 15)^2 + 15^2} = 49{,}4536\ mm$$

We have all the parameters to start the calculation of the volume of each part mentioned before and then we will just add them all to obtain the total volume.

5.1.3.1. Heart volume

Feeding zone's heart volume

The shape of this part is a cylinder:

Volume = $A * L_1 = (\pi \cdot 4{,}5^2) * 33 = 2070{,}74153\ mm^3$

Compression zone's heart volume

This part has a tronco conical shape, being his smallest area the same one that in the feeding zone and the biggest ares like the metering zone area.

Volume = $\frac{\pi}{3} * L_2 * (r^2 + r * R + R^2) = \frac{\pi}{3} * 52 * (4{,}5^2 + 4{,}5 * 6{,}5 + 4{,}5^2)$ = 5015,39559 mm^3

Metering zone's heart volume

The shape of this part is a cylinder:

Volume = $A * L_3 = (\pi \cdot 6{,}5^2) * 65 = 8660{,}7819\ mm^3$

So the total volume for the heart threaded zone is 15746,919 mm^3.

5.1.3.2. Filet volume

As is has a spiral shape which seems difficult to calculate, we have calculated the lenght of one filet turn before the volumes calculations despite the zone where we are referring to. After this, we only need to multiplied it by the section area (at the same time a product of the clearance and the ridge width) and also by the number of turns of the section. With the prodecure we are going to calculate the three zones filet volume.

Feeding zone's filet volume

$Volume = A * X * turns = (1{,}8 * 3) * 49{,}4536 * 2{,}2 = 579{,}497574$ mm^3

Compression zone's filet volume

In this case, for an easier way to calculate the volume we are going to divide it in two parts: the cuadrangular prism and the triangular prism, as seen in the following picture:

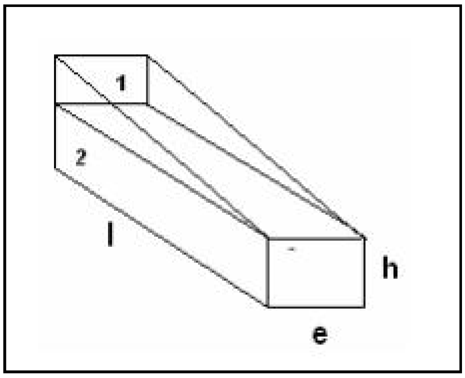

Figure 25. Compression zone filet geometry.

$$A_1 = e * \ (h_1 - h_2) = 1{,}8 * (3 - 1) = 3{,}6 \ mm^2$$

$$A_2 = e * h_1 = 1{,}8 * 3 = 5{,}4 \ mm^2$$

$$Volume = \frac{(A_1 * X * turns)}{2} + (A_2 * X * turns) \ = \ \frac{3{,}6}{2} + 5{,}4 \quad * 49{,}4536 * 3{,}4 = 619{,}55501 \text{ mm}^3$$

Metering zone's filet volume

$$Volume = A * X * turns = (1{,}8 * 1) * 49{,}4536 * 4{,}4 = \ 387{,}221881 \text{ mm}^3$$

Adding the three zone's filet volume we have a total volume for it of 1586,27446 mm^3.

5.1.3.3. Unthreaded zone volume

With the measures mentioned before we can easily obtain this volume by subtracting to the total volume the hole volume to attach the motor to the screw.

$$Volume = \{[(\pi * Dext^2)/4] * Lext\} - \{[(\pi * Dint^2)/4] * Lint\} = 3663{,}882432 \ mm^3$$

We can conclude saying that the total volume of the screw is approximately 20997,0759 mm^3 , and taking into account that the steel's density is 7700 kg / m^3 we reach to know what we want to calculate. The total weight of the screw is:

$$m = Volume * Density = 20997{,}0759 * 7700 * \frac{1 \text{ m}^3}{10^9 \text{ mm}^3} \ = \ 0{,}16167748 \ kg$$

As the total weight is below 200 g, we can consider the screw dimensions valid. We tried to minimize the weight of the extruder's head and all its components and we reach this dimensions, that are between the limits we wanted in terms of volume and weight.

5.2. Nozzle parameters

The last part to dimensionless the extruder is to delimit the nozzle's parameters. Taking into account that the entrance diameter is related with the metering zone diameter and the clearance in this part and we want a printing diameter of 0,4 mm, we have thought about this measures for the nozzle:

Nozzle entrance diameter: d_0 = $D + 2 * \delta$ = $15 + 2 * 0{,}003$ = 15,006 mm

Nozzle exit diameter: d_1 = 0,4 mm

Conical part noozle lenght: l_1 = 8,0025 mm

Cylindrical part nozzle lenght: l_2 = 2 mm

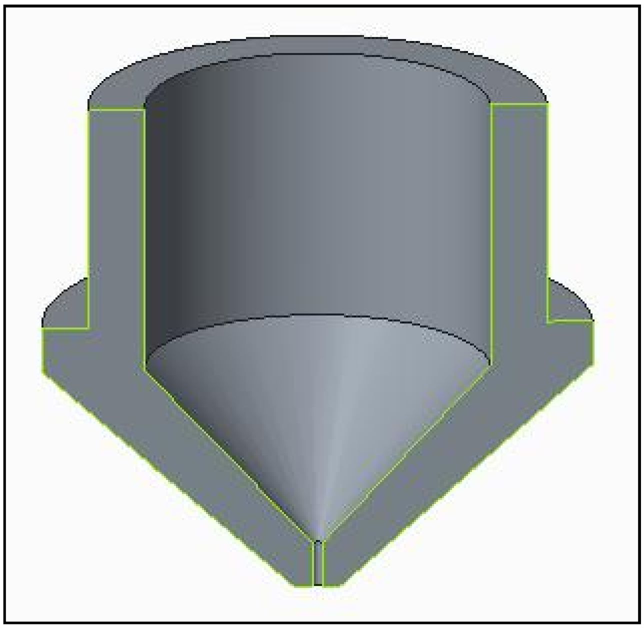

Figure 26. Nozzle section.

6. Extruder operating parameters

Now that we have checked that the dimensions and weight of the main components of the extruder fit in our claims, we are going to calculate the production that this design will have in an ideal process. If the obtain values are within the range we want, we will be able to start designing the different parts of the extruder in a 3D simulation program.

6.1. Flow rate

One of the most important parameters in a 3D printing process is the quantity of material deposited in the plate, comparing it to the time is needed for it. The magnitud that refines it is the volumetric flow. Production expressed as volumetric flow (Q) is the result of three different types of flow: the drag flow, the pressure flow and the filtration flow. Each flow has a coefficient related to the volumetric flow as the following formula shows:

$$Q = \frac{\alpha K}{K + \gamma + \beta} \eta$$

But the volumetric flow does not only depend on this parameters; also in the geometry that the nozzle has (measurements obtained in the previous section) and in the speed of the screw. We are going to explain how this parameters are related to the volumetric flow and how we calculated them.

6.1.1. Drag flow.

The α in the formula represents the drag flow coefficient. It is the largest component caused by turning the screw. The plastic enclosed between the spindle and the cylinder is forced to advance in axial direction. It can be calculated with this equation:

$$\alpha = \frac{\pi * m * D * h * \frac{t}{m} - e \; * cos^2\varphi}{2}$$

In the previous section we calculate all the necessary parameters to be able to solve the equation. But we are going to name them again the involved values:

Screw diameter: D =15mm.

Pitch: t =15mm.

Channel depth:h =1mm.

Helix angle: φ =17.65º.

Ridge width: e =1.8 mm.

Number of channels: m = 1.

Solving the formula with our parameters we obtain the following value:

$$\alpha = \frac{\pi * 1 * 15 * 1 \left(\frac{15}{1} - 1.8\right) * cos^2 17.65}{2} = 847.276\ mm^3$$

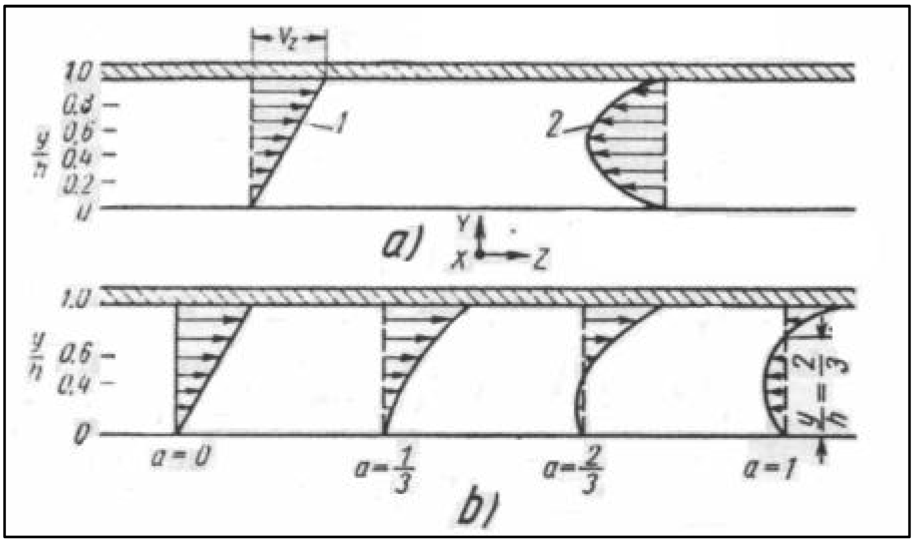

Figure 27. Flow direction. a)Drag flow. b)Pressure flow.

6.1.2. Pressure flow.

The β in the formula represents the pressure flow coefficient. Pressure flow appears against the main flow, that is in the opposite direction of the end. It is very important to design properly the screw so the pressure flow is lower that the drag flow, otherwise the extruder won't have any production flow, as it will go in the opposite direction. The equation that relates the screw parameters with this coefficient is:

$$\beta = \frac{\pi * h^m * \left(\frac{t}{m} - e\right) * sen\varphi * cos\varphi}{12 * L}$$

Where:

Screw length: L = 150 mm.

The rest of the parameters are the same that we used to calculate the drag flow coefficient.

Introducing our data, we obtain the following value for the pressure flow coefficient:

$$\beta = \frac{\pi * 1^1 * \left(\frac{15}{1} - 1.8\right) * sen17.65 * cos17.65}{12 * 150} = 0.057\ mm^3$$

6.1.3. Filtration flow.

The γ in the formula represents the filtration flow coefficient. It is produced by the loss of material between the clearances of the screw cylinder. The filtration flow coefficient represents the portion of fluid that seeps between the crest of the screw and the cylinder wall. The following formula delimits its value:

$$\gamma = \frac{\pi^2 * D^2 * \delta^3 * tan\varphi}{10 * e * L}$$

Where:

Filet clearance: δ = 0.03mm.

The rest of the parameters are the same as in the previously calculated flows.

As a result, we obtain:

$$\gamma = \frac{\pi^2 * 15^2 * 0.03^3 * tan17.65}{10 * 1.8 * 150} = 7.066 * 10^{-6} mm^3$$

6.1.4. Head geometry.

The K in the formula represents the head geometrical constant. To determine the constant K, the head is divided into successive zones of different settings, setting for each of these areas a different constant (K_i). Our head is divide in two different zones, one conical and the other one cylindrical.

- For the conical section calculation is used the following formula:

$$k_1 = \frac{3 * \pi * d_0^3 * d_1^3}{128 * L_1 * (d_1^2 + d_1 * d_0 + d_0^2)}$$

Where we have all the nozzle parameters calculated before:

L_1: length of the section. L_1=8 mm.

d_0: Initial diameter of the section. d_0=15.06 mm.

d_1: end diameter of the section. d_1=0.4 mm.

So we can just replace this values into the equation:

$$k_1 = \frac{3\pi * 15.06^3 * 0.4^3}{128 * 8 * (15.06^3 + 15.06 * 0.4 + 0.4^2)} = 0.008635$$

- For the cylindrical section is used:

$$k_2 = \frac{\pi * {d_2}^4}{128 * L_2}$$

We have all the values needed from the previous section:

d_2: diameter of the channel. d_2=0.4 mm.
L_2: length of the section. L_2=2 mm.

$$k_2 = \frac{\pi * 15.06^4}{128 * 2} = 0.0003142$$

- The real geometrical constant of the head is calculated in the next way:

$$K = \frac{1}{\sum\frac{1}{k_1} + \sum\frac{1}{k_2} + \cdots + \sum\frac{1}{k_i}}$$

With the values calculated for the conical and cylindrical part, we obtain:

$$K = \frac{1}{\frac{1}{0.008635} + \frac{1}{0.0003142}} = 0.000303$$

6.1.5. Volume flow

Right now, with the drag flow, the pressure flow and the filtration flow coefficients and the head geometrical constant we can know the relation between the volumetric flow and the screw speed. As we want to keep the volumetric flow like in the existing machine, we are going to make an experimental test to calculate its value. Then, we will fix this value and calculate the unknowns with their relation with the volumetric flow.

For the experimental test we set the printer and print a piece of 20x20x1 mm to print a volume of 400 mm^3. We control also the time while printing so with the volume, the density and the time we can obtain the flow rate. We made this process a few times and take the average of the results to be more precise in the obtained results.

The density of the material (PLA) is: $\rho = 1.3 * 10^{-6} \, kg/_{mm^3}$

The average time for the experiment was : t = 107,183 s

So with this free parameters we can calculate both, the volume flow and the mass flow:

Volume flow rate: $Q = Vx\frac{1}{t} = 3.732\frac{mm^3}{s}$

Mass flow rate: $\dot{m} = \rho \, x \, V \, x \, \frac{1}{t} = 4.852 * 10^{-6} \, kg/_s = 2.911 * 10^{-4} \frac{kg}{min}$

6.2. Screw speed

We have calculated all the necessary parameters to determine the production of our extruder. We only need to determine the speed of rotation of the screw. We use the flow experimentally obtained and the flow equation to determine the rotational speed. However, the calculated flow will be multiplied by a safety factor of 1.25 to ensure that production is greater than or equal to the desired.

$$Q = \frac{\alpha * K}{K + \gamma + \beta} n \text{ ì } n = \frac{Q}{\frac{\alpha * K}{K + \gamma + \beta}}$$

Where, as previously obtained:

Flow rate: $Q = 1.25 * 3.732 = 4.665 \frac{mm^3}{seg}$

Drag flow coefficient: $\alpha = 847.276\ mm^3$

Pressure flow coefficient: $\beta = 0.057\ mm^3$

Filtration flow coefficient: $\gamma = 7.066 * 10^{-6} mm^3$

Head geometrical constant: $K = 0.000303$

So we replace these values in the equation and we calculated the screw speed as:

$$n = \frac{4.665}{\frac{847.276\ * 0.000303}{0.000303 + 0.057 + 7.066 * 10^{-6}}} * \frac{60\ seg}{1 min} = 62.5\ rpm$$

6.3. Required power

The power required symbolizes the speed with which a job is carried out. This power has to be provided by the motor to the screw. It can be calculated using the following energy balance:

$$N = 32 * 10^{-5} * Q * C * (T_m - T_0)$$

Where:

Flow rate: $Q = 1.25 * 3.732 = 4.665 \frac{mm^3}{seg}$

Heat capacity of the PLA: C = 1386 J/Kg·K.

Inlet temperature: T_0 = 20ºC.

Outlet temperature: T_m = 200ºC.

The inlet temperature is the average room temperature, so the temperature of the material before enter in the extruder. The outlet temperature is the temperature which the material will have while being printed. We calculate the required power as:

$$N = 32 * 10^{-5} * 4.665 * 1386 * (200 - 20) = 372.424\ W$$

6.4. Maximum pressure

The pressure in the extruders is generated in the metering zone and it plays an important role in the process and in the material surface finish. In addition, it is important because different calculations for the design of the machine are derived from the pressure.

To calculate the maximum pressure, we consider zero flow, so the drag flow becomes also zero. We use the next formula:

$$Pmáx = \frac{6 * \pi * D * L * n * \mu}{{h_1}^2 * \tan \varphi} = \frac{6 * \pi * 15 * 150 * \frac{62,5}{60} * \mu}{3^2 * \tan 17,65}$$

To obtain the maximun pressure, first we need to calculate the viscosity, which depends on the shear rate.

6.4.1. SHEAR RATE AND VISCOSITY

Experiments have limited the value of the shear rate of plastic between the range 100 s^{-1} to 1000 s^{-1} for extrusion processes. In *Figure 28* it is shown the interval of shear rate that normally the diffrent processes have:

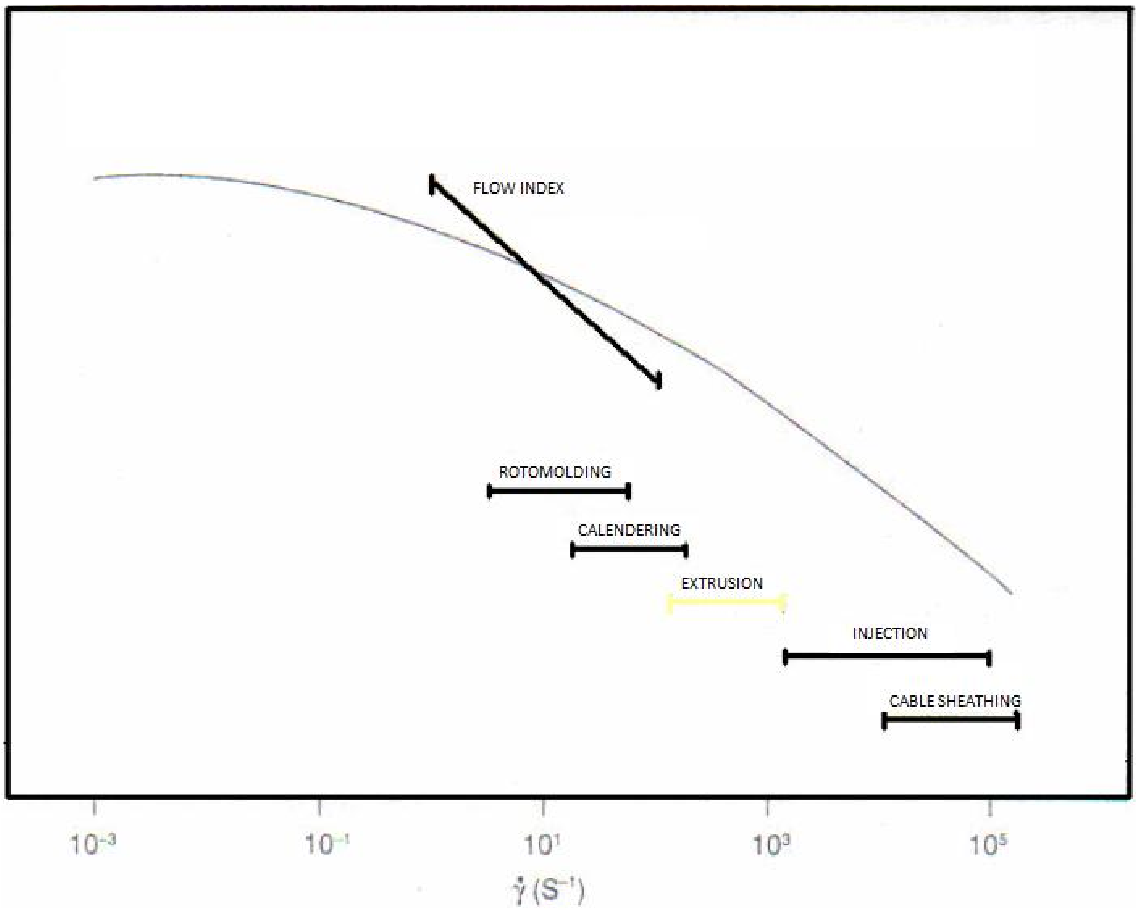

Figure 28. Shear rate intervals for different processes

We choose the value of 100 s^{-1} as the limit for calculating the minimum working conditions. With this value we can now obtain the viscosity of the polymer, which depends aswell on the temperature, as shown in *Figure 29*. In our 3D printer we will have a temperature of 200 ºC, as it is the average temperature to print PLA, so with this values we obtain a viscosity if 650 Pa·s.

We are now able to calculate the maximun pressure with the previous formula:

$$P_{máx} = \frac{6 * \pi * D * L * n * \mu}{{h_1}^2 * \tan\varphi} = \frac{6 * \pi * 15 * 150 * \frac{62,5}{60} * 650}{3^2 * \tan 17,65} = 1 \cdot 10^7 Pa = 98,97\ bar$$

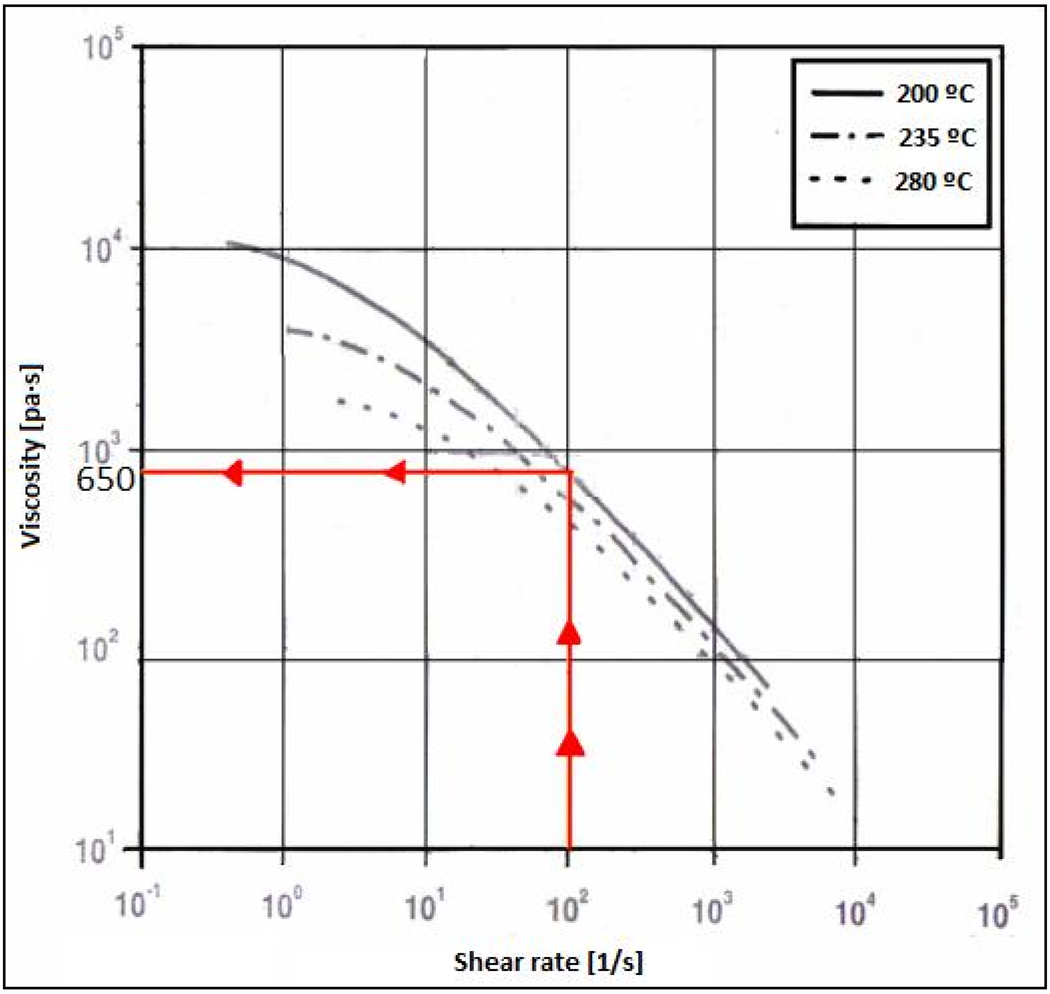

Figure 29. Relation between shear rate and viscosity.

6.5. Printer speed

With the parameters of the 3D printing process we have obtained, we can calculate the speed of the head while printing. This speed can be controlled by the engine's angular speed, so it is useful to know it and then use it as a reference so if we want a higher volumetric flow we will have just to increase the engine's speed.

For this calculation, we have to make a small test. We are going to aproximate the printer's output area as a rectangle, so when the material is printed it will form a rounded corner rectangle but we will consider this corners negligible so we have a simpler area to be calculated. So the flow and the printer speed are related to each other by this parameter and by the height you want to give to the layer (parameter that can be chosen by the user when deciding the printing parameters values). We are going to calculate it for a height of 0,2 mm because it was the value that we used in the flow's calculation test. With all this mentioned parameters, we obtained:

$$Q = w * h * v_e \rightarrow \ v_e = \frac{Q}{w * h} = \frac{4{,}665}{0{,}4 * 0{,}2} = 58{,}375 \ mm/s$$

This is the extruder speed for the inner layers, but for the first layers there is other speed because their height is bigger as they are used to form the outline and base of the piece. Basing the test in the existing machine, we consider a printing height of 0,25 mm for the first layers. The speed obtained is shown below:

$$Q = w * h * v_e \rightarrow \ v_e = \frac{Q}{w * h} = \frac{4{,}665}{0{,}4 * 0{,}25} = 46{,}7 \ mm/s$$

These speeds have been calculated as references. In all the 3D printers, the speed that they have varies depending on the zone (for example, they use higher speed in the inner layer than in the outer ones) but we consider these values as an average of the printing process.

7. Element's design

This section will show the 3D design of the different elements of the redesigned head and its characteristics such as the material, how they will be joined to the rest of the elements, how they will keep the temperature and the reasons for designing them in this particular way.

The 3D designs have been designed in the software Creo Parametric. As it is a program specialized in this kind of volumetric designs, we will just attach the pictures into this memory to show up the obtained result.

7.1. Screw design

In the section 4 and 5 we calculated the dimensions of the screw and the flow and angular velocity that it will have for these measures. As it is the most important element of this redesigned head, we previously proved that all the parameters give the pretended result and for this reason we were able to design the screw, knowing that it is correctly dimensioned.

7.1.1. Solid model

In the section 4 the screw dimensions were mentioned and calculated, but we are going to detail the most important ones and show the result of the 3D model. As said before, we chose a screw diameter of 15 mm and a threaded lenght of 150 mm for keeping it as small as possible. In the same way, we add a 25 mm unthreaded part that will be inside the hopper to be attached to the engine. The designed model is as follows:

Figure 30. Screw solid model in CREO Parametric.

7.1.2. Material

There are two basic characteristics that it should satisfy in order to perform his function correctly: to be hard enough to be aware of the possible erosion and to be able to handle with high temperatures, which will be caused by the movements that the screw itself has, the friction against the cylinder and the heating system.

For these reasons, the material chose for the screw is steel F-174, which is a nitriding steel. This material reaches vickers hardness of 1048-1064 HV, suitable not to be eroded and to maintain its function for a long life period, as one of the main characteristics for nitriding steels are to improve the corrosion and fatigue resistances for the common steels.

In addition, it is able to handle with the high temperatures reached inside the extruder. During most of its lenght it has to be around 200ºC, so a nitriding steel fits perfect for this function as they are designed to endure with temperatures till 500ºC.

7.1.3. Movement system

The movement of the screw will be given by the engine. The screw will be attached to it in its highest part in its position in the 3D printer. It has to be as tight as possible in order not to be a gap between both elements. With this premise the movement will be given directly from the engine to the screw, so controlling the engine's angular velocity we can adjust the exact angular velocity that we want for the screw.

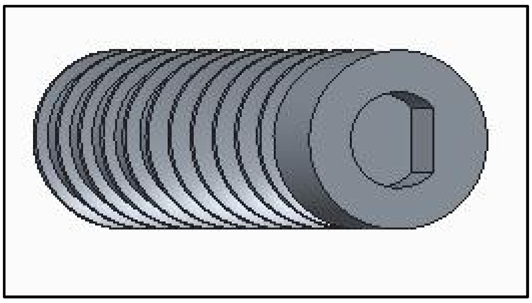

Figure 31. Detail of the screw connection.

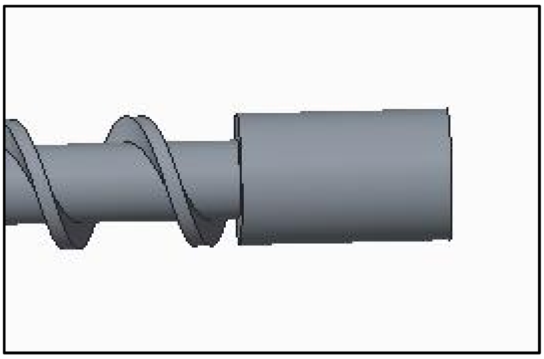

Figure 32. Movement transmition in the screw.

The hitch has been designed to fit with the motor shaft, so that no fastenings elements are needed between. In addition, it has taken advantage of the disposition of the screw using the screw itself as filler material aid. For it the lengthof the feed zone of the screw, previously calculated, has been extended so it gets into the hopper and forces the plastic powder to get into the extruder.

7.2. Nozzle design

The nozzle dimensions were also mentioned in section 4, as they are an important part of the head design in terms of functionality. But in this point we will analyze a bit more about it, mencioning the material and its characteristics and its way to be attached.

7.2.1. Solid model

Going quicky to the dimensions, we can say that the initial inner diameter is 15,06 mm, because of the clearance that we have to give between it and the screw, and the final inner diameter is 0,4 mm, because is the printing area size that we need. The lenght for the final inner part is 2 mm. This measure is also very important because it has to be as small as possible because is where the material comes out, but not to much in other that the flow isn't able to drop with a conical shape. The 3D model has this aspect:

Figure 33. Nozzle solid model in CREO Prametric.

The conical shape is inspired by the most of nozzles in the market. It is made on purpose to prevent the plastic from sticking on the nozzle so the plastic comes out of the printer cleanly. A very common problem when printing is precisely that the plastic sticks to the head rather than deposited on the base.

The way to attach the nozzle to the extruder is designing it as a continuation of the cylinder. The threaded part will be the same in both of them: the exterior diameter. With this we just need a female thread that is able to join both of them. The nozzle has to be the last element to be threaded because it has a bigger diameter as a stop for the thread.

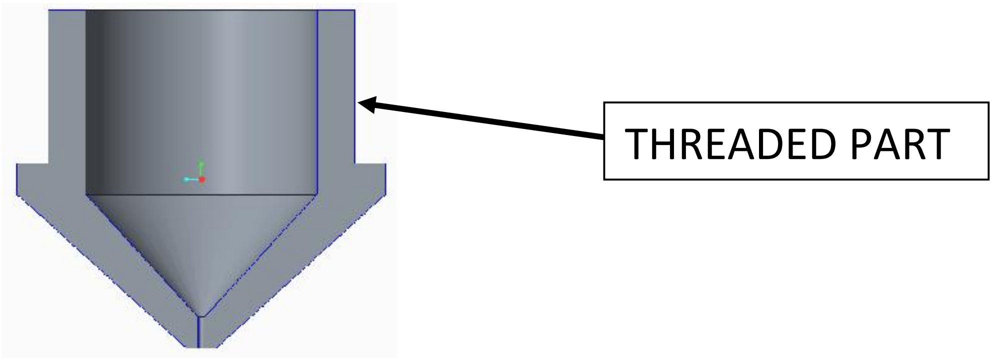

Figure 34. Nozzle's half section.

7.2.2. Material

The material most commonly used for nozzles is brass because it has to withstand high temperatures. Likewise, is a good conductor of heat, quality that is needed to heat fast and uniform the nozzle as the printing material needs to be printed around 200ºC. Similarly, the material chosen for our nozzle is brass.

Brass is one of the material with best characteristcs and this is why we are choosing it for the nozzle, also one of the most important elements of a 3D printer. Between his characteristics we are going to remark its hardness and the fact that it perfectly keeps its conditions for a long period of time. Also, it doesn't get affected by the external conditions. Its has the characteristics of the best materials in the market but with a lower price.

7.3. Cylinder design

The cylinder is the part in charge of keeping the material inside while going throughout the screw. It has to be designed as to fit in this purpose, so for this reason its inner diameter is the sum of the screw diameter and the clearance, to be a total of 15,06 mm. Its total lenght to be able to cover all the screw is 140 mm.

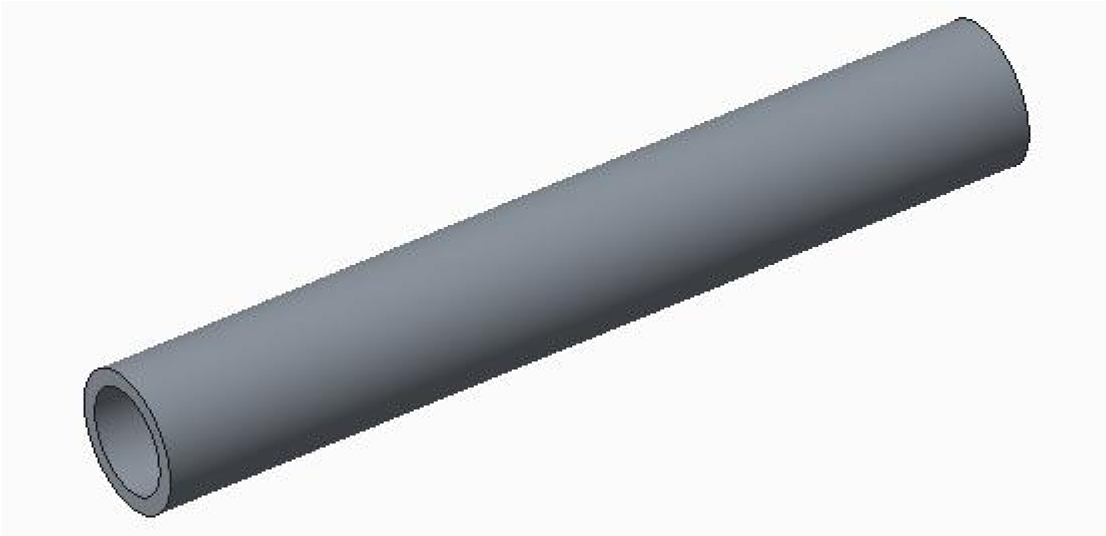

Figure 35. Cylinder solid model in CREO Parametric.

The cylinder is threaded on its exterior surface. It will be threaded in the heaters so it gets fixed and join to the nozzle, as mentioned while explaining the nozzle, and it will cover the screw. On the inner surface a very slick finish is not necessary, since the fact that a certain roughness improves the flow of the plastic and the mixture inside the extruder. On the top part of the cylinder a teflon joint will be engaged on the cylinder.

In the same way as for the screw the material chosen for the cylinder is steel F-174, for the same reasons. The cylinder should also be able to handle with high temperatures and be hard enough to resist degradation due to the friction generated between the inner face of the cylinder and the plastic flow.

7.4. Hoppers design

7.4.1. Hoppers 3D models

The hopper is the element in charge of storing the plastic granulates and guide them into the feeding zone of the extruder. In the existing machine, as in many other designs, only one big hopper is placed at the beginning of the extruder. However, in this case we have two hoppers connected between each other. The main reason of this decision is that we want to make the head's assembly as small as possible because it is the part that will be moving during the printing process. So with this premise, we have designed a small hopper attached to the extruder and a bigger one outside from the head assembly to have more storage. The extruder's hopper 3D model is shown below:

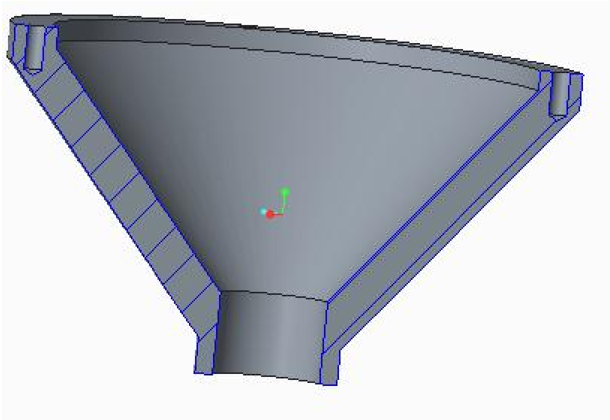

Figure 36. Hopper's half section solid model in CREO Parametric.

This hopper is continuously feed from the top, thanks to the connection through a flexible plastic tube with the upper hopper. Unlike the large hoppers of the common extruders, this hopper is not capable of holding large amounts of material. But, it will not be necessary to stop the printing process every time to fulfill this hopper.The flexible connection between the two hoppers allows the upper hopper feed the hopper of the extruder even when in motion. Thus we managed to print performing a continuous process, because we only have to fill the upper material hopper, which can be done at any time while printing is taking place. As it has been said before, the hopper houses inside the connection between the engine and screw, which reduces the volume available to the feed material, making more necessary the second hopper. In the next figure you can see how the hopper will be feed. The plastic tube, which guides the material into the hopper, will be attached to a plate placed over the hopper.

For the upper hopper we have decided the dimensions so then we can calculate for how much time could the process long without refilling the hopper with more material. It is actually an element that can vary a lot depending on the pretensions of the user. The shape in this case will have the conical part, as in the lower hopper, and also a cilindrical part to make it bigger and to be able to have a bigger material storage. So we chose an inner diameter of 100 mm, an angle of 60º for the conical part and a height of 50 mm for the cilindrical part. With this dimensions and aproximating the flexible connection diameter to 0, we find out that the total volume of the hopper is 619424,002 mm^3/s. Now that we know the total volume and the flow that the machine will have, we can easily calculate the time that the process can be working without refilling it as:

$$t = \frac{Volume}{Flow} = \frac{619424{,}002\ mm^3}{4{,}67\ mm^3/\ s} * \frac{1\ h}{3600\ s} = 36{,}84416\ h$$

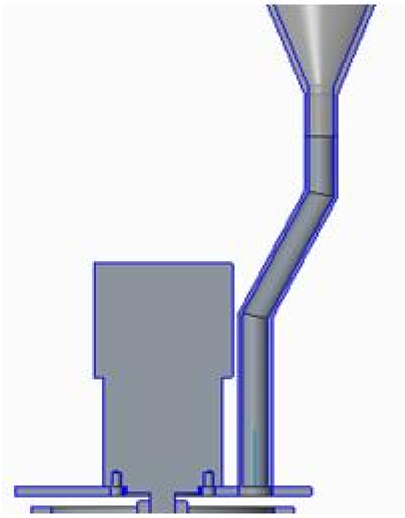

Figure 37. Feeding system scheme.

Moreover, the hopper will also serve as support for the engine that will turn the screw. As shown in the previous figure a plate fixed on the hopper will support the engine and fixe it to the printer head. The plate is fixed to the hopper with screws, and the engine is fixed to the plate also with screws.

7.4.2. Hoppers' materials

The extruder hopper will be made in Corzan (CPVC), because it is resistant to corrosion and temperature and easy to manufacture. In addition, it is also used sometimes as an isolate material, which helps to keep the feed throat to the extruder cold. In general, it has much better properties than the PVC such as manufacturability, easy maintenance, low weight, waterproof,..., and as it is an important part of the process, we decide to invest more money in a material with good characteristics.

The other hopper, located on the top of the machine, will be fabricated in Polypropylene (PP), because it is a cheap material and also lighter. Of the materials that fit in this two characteristics, we decided to use Polypropylene because of its manufacturability and because is easy to stick it and fix it.

7.5. Engine design

7.5.1 Engine choice

For the engine we wanted to choose an existing product in the market, so we don't have to design it ourselves. We were looking for the simplest and cheapest one for the needed specifications. After a market study, we found out some useful conclusions. Most of the 3D printers use Nema motors, which are step by step engines with quality guarantee. Also, we decided a step for the engine of 1,8º (0,9º steps are only used for very precise 3D printers and it is not our case) and a logical intensity for our case (1,7 A is the most adjustable one).

In addition, the operating torque depends on the load needed. In our case we considered a light-weighted load, so the torque has o be between 0,28 N·m and 0,4 N·m. Of course, one of the most important parameters in our case is the dimensions that the motor has, because we are trying to make an extruder as small and light as possible.

For all this reasons we chose the following engine and reductive:

- NEMA17 Motor: 42HS40-1704Z.

  Reductive: 36PLGB2-xxZ

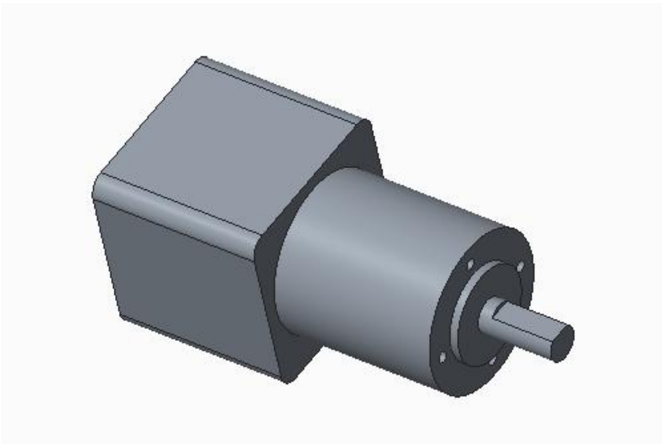

Figure 38. Engine solid model in CREO Parametric.

7.5.2. Engine specifications

The dimensions are detailed in the Annex ?. As mentioned before the engine is attached to the screw by introducing its shaft into the screw's hole. This gives the extruder its movement. The engine is aswell attached to a fixing aluminium plate by the four threaded holes that it has. Four screws will be threaded there to prevent the translational movement of the motor. It is also a way to attach the screw to a fixed base.

7.6. Fixing system design

As we have been saying during the memory, our intention is to attach the redesigned head to the already existing vertical plate. In this way is easier to find the way that both pieces move together as we can base our way to do it in the actual one and get it better if we consider that it should be. So what we have called fixing system, it is just the elements that we have designed to attach our assembly to the machine.

For this aim we will use a plate that is able to have holes and everything necessary to screw it into the existing vertical plate. Although the main goal of this fixing plate is to attach the head to the rest of the machine, it will also hold the fans that cool the cylinder down to control the temperature inside. Moreover, it also has to hold the layer fans support, which we will explain them in the next point. Therefore, the pieces we have to design should perform simultaneously three different functions.

To start designing the pieces we looked at the machine in which we are going to assemble the extruder, and which we have already described it. This machine has a vertical metal plate with holes prepared to screw the head and all its components at different heights. This allows us to adjust the designed assembly to the height we pretend, so the designed of the fixing plate can be more flexible. With all the mentioned conditions, we thought in a plate with three different parts. One part with the holes for the screws to attach it into the vertical existing plate, other part with four holes for the bolts of the layer fans support and a hole to pass through the cylinder and the last part to assemble the fans for the cooling system. We can see the final aspect of the plate in the picture that follows:

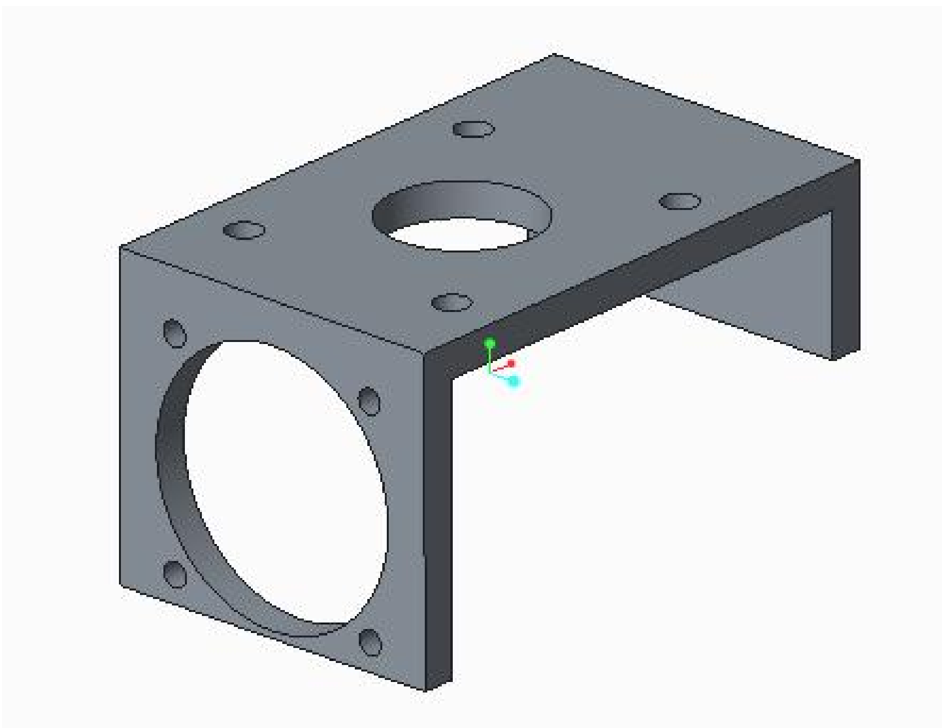

Figure 39. Fixing plate 3D model in CREO Parametric.

The plate is made in aluminum of 5 mm of thickness because it is a cheap and easy for folding and drilling material but enough resistant to be rigid during the printing process. It is also resistant to high temperatures, that is a mandatory condition for the place where is located. The rest of the pieces that are threaded to the cylinder can be tightened to it to ensure that the fixing piece will not move. Then, the piece is screwed to the plate of the machine being fixed and integral with the movement of the extruder machine. The fans will be simply bolted to the plate.

As with only one piece it would not be enough to fix the extruder, we will make two of them. They will be exactly the same as we have two fans, one for each zone of the heating system, that will have to be attached to these plates. The last function that the fixing plate has is, as mentioned, to attach the layer fan's support and this will be done only with the lower fixing piece, but the design wouldn't change but it will make the process longer than to make both in the same way.

7.7. Heating system design

In this section we are going to describe one of the main points of the extrusion process: how are we going to achieve the pretended temperature in each part of the extruder. For this purpose we are going to need a heating system to higher the temperature along the cylinder but also a refrigeration system to lower the temperature when it gets very high and an insulating system in order not to let the hot passes to some zones. We are going to explain these three different parts below.

7.7.1. Heating system

When the extrusion process starts, as there is not yet friction between the screw and the cylinder, it is necessary to provide heat to the cylinder so that the enclosed plastic warms up too until it melts. This is the only way to restart the extruder. If the plastic enclosed inside does not melt, the screw is blocked and the extruder cannot be turned on and begin the process. For this reason, we had to include a system of heaters to provide the necessary heat on the cylinder to melt the plastic located inside it. It will also be necessary an element that controls that the temperature doesn't rise too much, but this system will be explained in the following point.

As there are many elements to take into account, the design of this heating system and temperature control is one of the most difficult parts of the project proposal. In addition, the traditionally used systems for heating and cooling the cylinder in common extruders are too big and they will increase the size of our printer head a lot. Therefor we had to think in a new system that could fix in our project.

For the system design the first thing we have done is think about how we warm the cylinder so it can have different temperatures in each zone of the extruder. For example, during the extrusion process the temperature in the compression zone is not the same as the transition zone. In extruders, heaters rings with electrical resistances are normally used, placed in each area in which a certain temperature is required. Together with one of these rings is also placed a fan which will cool the zone and to performs as the temperature control once friction begins to raise the temperature. However, this rings and fans are usually very big and we cannot include them in our design.

Figure 40. Example of rings heaters used in traditional extruders.

For our printer we have relied on both, the Delta Rocket hot end and the information collected in the book Printing in Plastic, where they explain how to build your own 3D printer. In the book it is explained how to mount our own hot end, including the necessary materials and the process to follow. The system consists of electric resistors coupled to a metal part, which will be the heater, in which the cylinder is inserted. The electrical heating elements heat up the metal piece and this in turn the cylinder. Thus it is achieved the heating and melting of the plastic inside the cylinder. In addition, the nozzle is also threaded into this metal piece, so it gets attached to the cylinder and heated, preventing the plastic from getting stuck in the end of the extruder.Besides the resistances, a thermal sensor is attached to the heater, that enables reading the temperature in the heater, and so control the temperature.

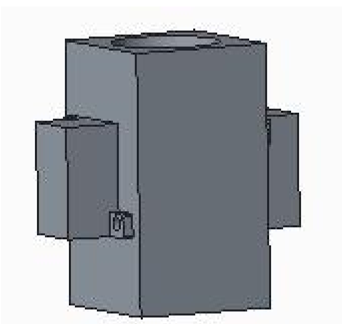

Figure 41. Heater system with the resistances attached.

In the figure, you can see the arrangement of the resistors in the heater piece. Positioning the resistances on opposite sides, it helps the heating of the workpiece to be more uniform and easier to control. In one of the free sides the temperature sensor will be placed, which It will enable the electronic system to control the temperature switch on or off the system when it is necessary.The resistance chosen are RH10 RE65G which gives us the energy necessary because it can work at temperatures up to 250 degrees and the process for PLA develops around 200ºC. The information data sheet of the resistance can be found on the annexes.

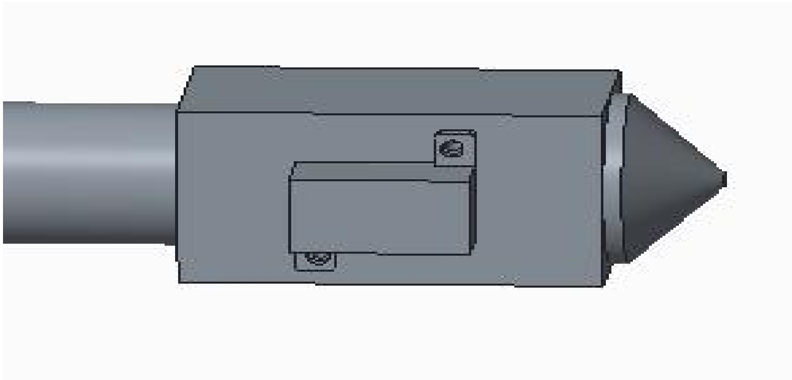

Figure 42. 3D model of the heater's assembly attached with the cylinder and the nozzle.

In this project, because the size is very small we believe that it will only be necessary to control the temperature in 2 zones, so we will add only two of these heaters, one for the compression zone and one for the metering zone.

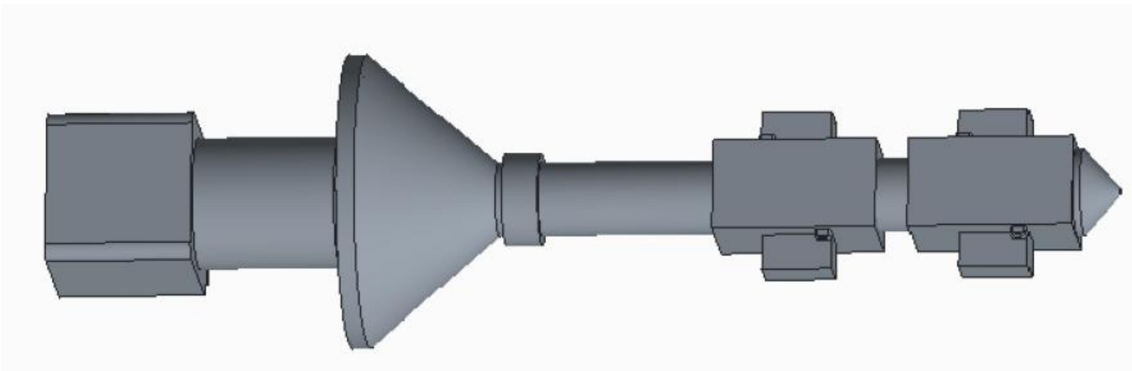

Figure 43. 3D model with the two heaters assembled to the cylinder.

Melting power needed to start an extrusion.

We are going to calculate the energy that is necessary to provide to the plastic to melt it. Although we have already chosen our resistances, ensuring that allow us to obtain the required temperature of 200ºC, as they can reach 250ºC, we think is also good to have an approximation of the power that they will need.

The power needed can be calculated with the next equation:

$$W = \rho * V * C * \Delta T$$

Where:

Power per second needed: W.

Plastic density: $\rho = 1.3 * 10^{-6} \frac{kg}{mm^3}$.

Volume: V.

Heat capacity of the material: C= 1386 J/Kg*K.

Temperature increase: $\Delta T = 200 - 20 = 180ºC$.

To calculate the volume enclosed inside the extruder we depreciate the volume occupied by the screw helix. In this way, the volume of plastic will be the difference between the volume of the chamber inside the cylinder and the volume occupied by the screw.

The volume of the hoe of the cylinder is:

$$V = l * \pi * r^2$$

Where:

Length: l=150mm.

Radio: D= 15.06mm.

So:

$$V = 150 * \pi * 7.53^2 = 26507.19\ mm^3$$

The volume of the screw will be divided in three different zones as it is in:

Feeding zone length: $L_1 = 33mm$ and $r = 4.5mm$.

Compression zone length: $L_2 = 52mmr = 4.5mm\ and\ R = 6.5mm$.

Metering zone length: $L_3 = 65mm$ and $R = 6.5mm$.

For the feeding zone the volume is the volume of a cylinder so:

$$v_1 = l_1 * \pi * r^2 = 33 * \pi * 4.5^2 = 2099.37\ mm^3$$

For the compression zone the volume is the volume of a trunk cone so:

$$v_2 = \frac{l_2 * \pi}{3} * (r^2 + R^2 + r * R) = \frac{52 * \pi}{3} * (4.5^2 + 6.5^2 + 4.5 * 6.5) = 4996.18\ mm^3$$

For the metering zone the volume is the volume of a cylinder so:

$$v_3 = l_3 * \pi * R^2 = 65 * \pi * 6.5^2 = 8627.6\ mm^3$$

Therefore, the volume of plastic that must be melted:

$$V_t = V - v_1 - v_2 - v_3 = 10784.04\ mm^3$$

So if we go back to the equation of the power:

$$W = \rho * V * C * \Delta T = 1.3 * 10^{-6} * 10784.04 * 1386 * 180 = 3497.52\ J$$

This value represents the heat to be provided by resistance, when starting the process, when all the material needs to be melted inside the extruder.

As we can see on the data sheet of the resistance, the resistances provide 12.5 watts. We have 4 resistances so we can give to the extruder 50 joules every second. So the time we have to wait until all the plastic is melted:

$$t = \frac{3497.52}{50} = 70 seg$$

This will be the time that the printer needs to be ready to print every first time we turn it on.

7.7.2. Refrigeration system

After turning on the extruder and the screw begins to rotate, the friction generated between the plastic and the cylinder generates additional heat which increases the temperature of the cylinder a lot. As we want a constant temperature of aproximately 200ºC, it is necessary to add to the extruder a cooling system that allows to control the temperature in the cylinder despite the heat generated by friction. This cooling system will consist in adding two fans close to each heater so the system will be activated whenever the temperature rises 200ºC.

Obviously these fans will not be placed on the heater surface as itwould heat up a lot and would not perform its function well. Following the example of existing extruders, the airflow is separated few centimeters from the heater. In this way it helps the action of air, so it cools more uniformly on all sides of the extruder, ensuring better temperature control. The fans chosen are: MULTICOMP MC36257. It is an axial fan, which works with 12 VDC, providing up to 0.226 m^3/min. The main problem with the fans is actually that we can't determinate before starting the machine how much air flow are we going to need. For this reason, we have chosen one fan that can be easily changed for another one more powerful with the same dimensions. In addition, the way the fans are attached to the system, it makes it very easy to change them by any other fan. More information can be found on the data sheet of this family of fans on the annexes below.

Layer fans support design

When printing PLA is important to add layer fans to the printer that cool down the plastic deposited on the base layer after layer. Just as the Delta rocket, it has decided to add 2 fans to perform this function. Therefore, it was necessary to design a completely new support that fits in our printer head.

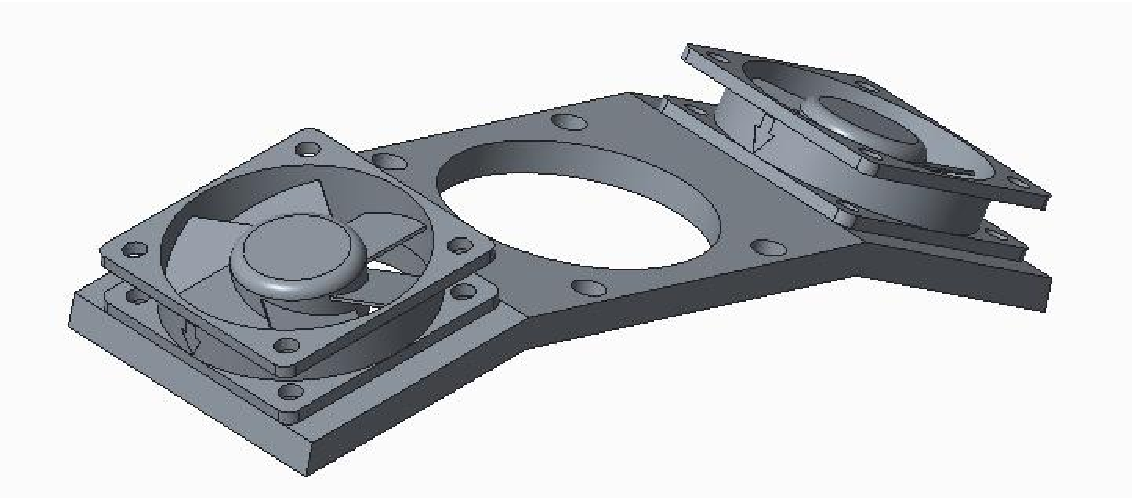

Figure 44. 3D model of the fans layer support with the fans assembled on it.

The design shown in the figure is inspired by the existing one on the delta rocket. It will be printed in PLA or ABS plastic, which makes it a very cheap piece. The piece has a hole in the middle so the nozzle fits in and two more in each side to allows the fans blow air on the printed plastic. The fans are fixed to the support by 4 screws each.The entire structure will be suspended in the air, held by four bolts on the plate that holds the extruder head to the three axis machine. This plate is the same which the cooler fans, from the heater system, are placed.

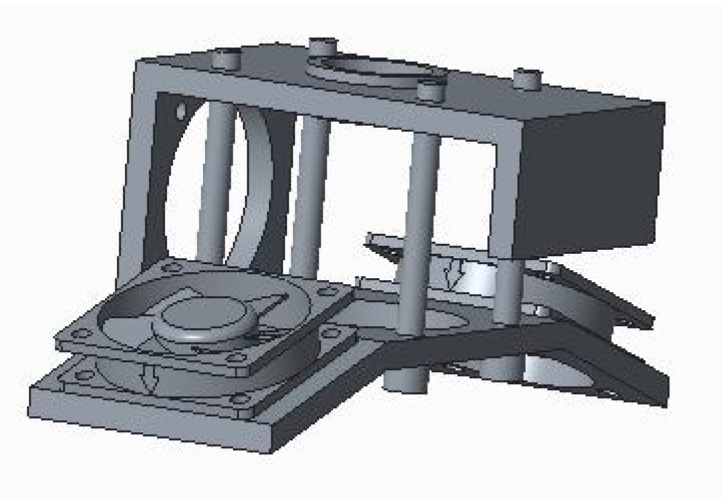

Figure 45. Assembly of the layer fans support with the four bolts and the extruder support

The details of the design can be found on the drawings of the annexes.

The fans chosen are the same as the delta rocket has: MULTICOMP MC36257. It is an axial fan, which works with 12 VDC, providing up to 0.226 m³/min. The technical data sheet for the fans can be found on the annexes below. The reason for choosing these fans and not others, is to try to change as few as possible the parameters with respect to the Delta rocket. Since the flow which we are working with is the same as in the Delta rocket, the fans should work under similar conditions as they do in the existing printer.

7.7.3. Insulating system

The purpose of this joint is to prevent the heat, due to the temperature at which the cylinder is heated during the process, reaches the hopper. Thereby we keep the feeding zone cold, preventing the plastic powder from sticking in the throat of the hopper.

For this reason, teflon has been chosen as the joint material, since it is a great insulator capable of withstanding temperatures up to 260 degrees without degrading.

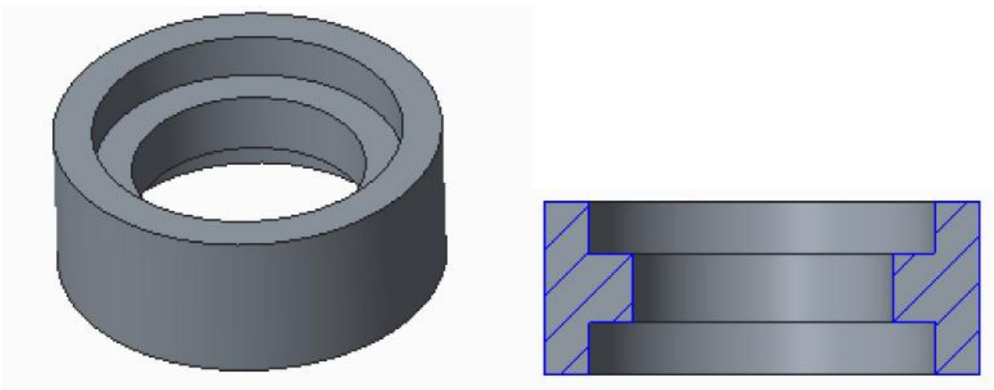

Figure 46. Teflon joint shape and section.

The joint will be embedded between the hopper and the cylinder isolating thermally both pieces.

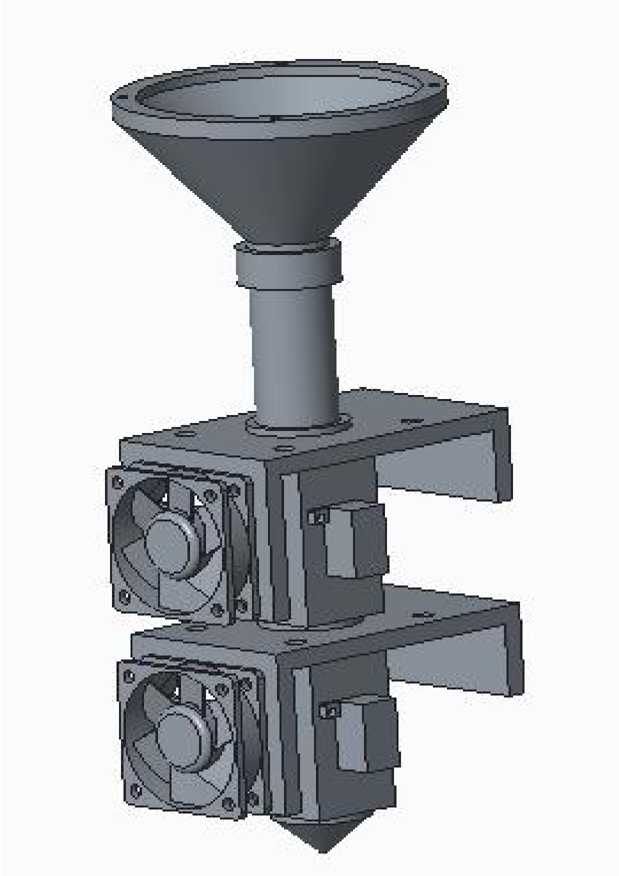

Figure 47. 3D model with the fixing system assembled. It is also visible the way the fans, from the cooling system, are attached.

We have also added a final piece to our fixing system. As we already mentioned the support part will be sandwiched between the two parts of the heater. This means that the heat of these parts is transmitted to the holder piece. However, on one part of the support will be placed the fan, which is made of plastic. So If the plate is too warm could melt the fan. For that it has been included a teflon joint which isolates the fixing piece from the heaters.

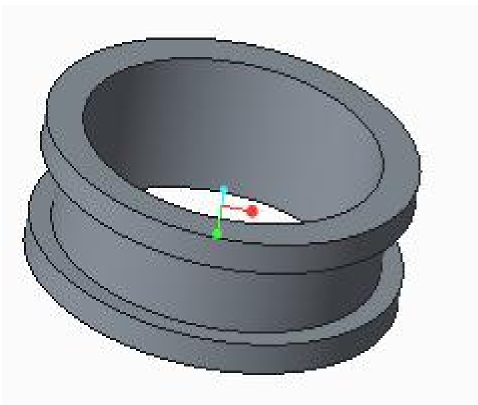

Figure 48. Teflon joint which isolates the extruder support from the heating system pieces.

This joint will be fitted in the hole that the plate has to pass the cylinder and the heaters. Due to its shape the heaters will rest on the joint instead of doing it on the plate, thus the transmission of heat is avoided.

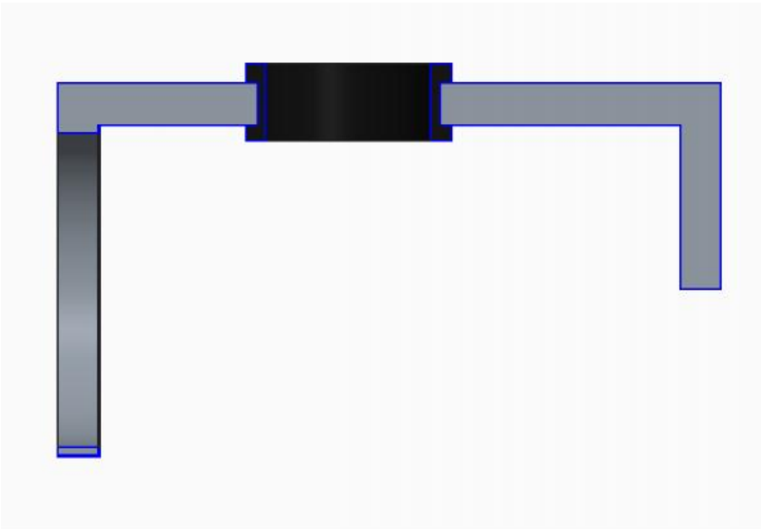

Figure 49. Section with the joint assembled to the plate

The material is the same material used for the other joint. It resists temperatures up to 260 degrees. More information can be found on the drawings in the annexes.

8. Assembly design

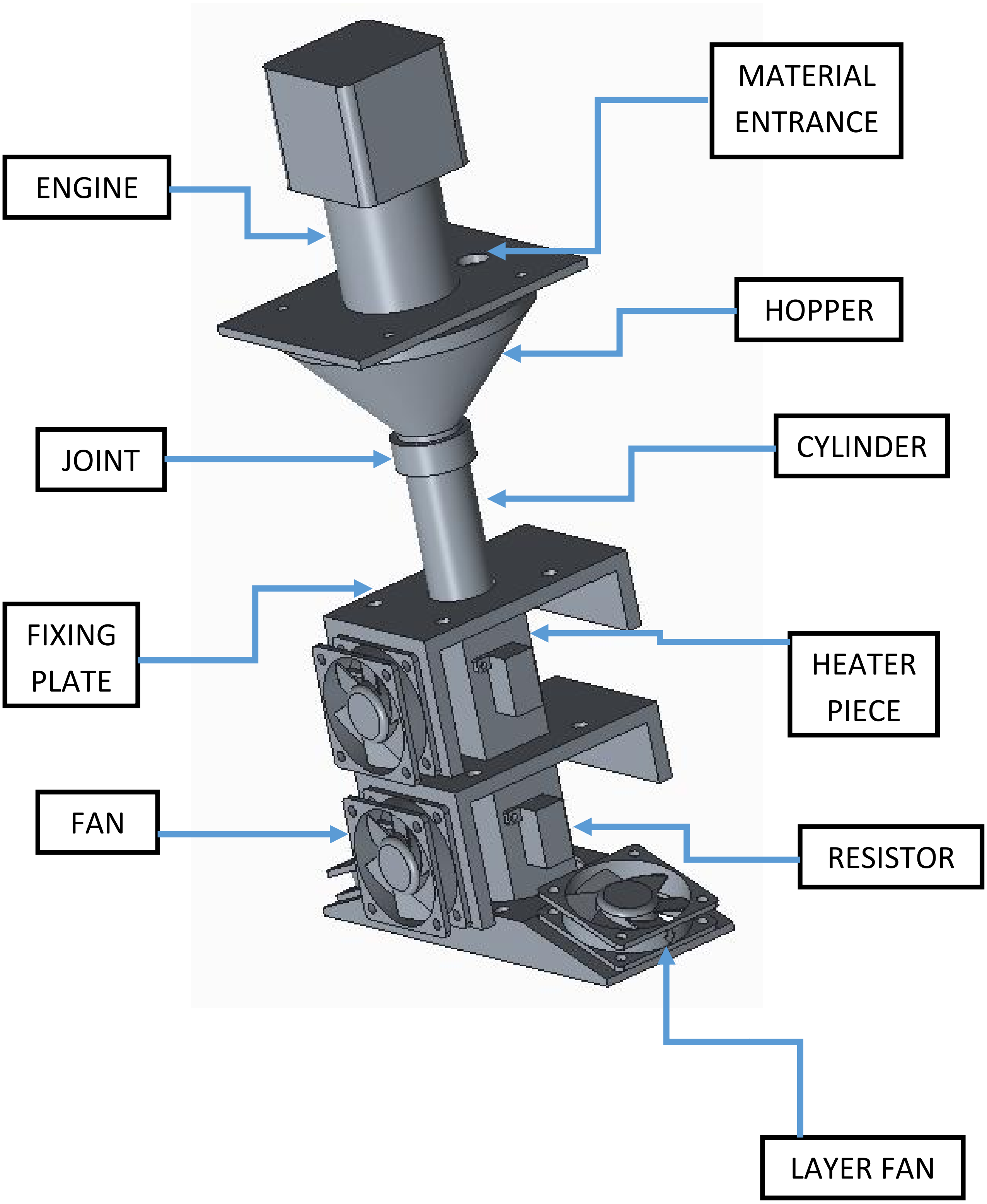

Figure 50. Extruder elements.

This is the general view of the assembly of the redesign of the printer's head. In it, each important element is indicated and only the connections between them, such as screws, threaded studs,..., are missing for simplicity while seeing the overview. As we had been saying throughout the memory the main points for this redesign are making the head as small as possible, design an extruder for been able to print starting from granulate plastic and control the temperatures along the whole process in order not to have problems of stagnation. We had already explained all the elements one by one, but in this section we will focus in the head as an assembly.

First of all we are going to explain how all the elements are connected between each other. We will proceed with the explanation ordering the assembly steps. In one side we have three elements: the engine, the plate where the material entrance hole is and the screw. The first step is to attach the engine to the plate by the four screws that the engine has in the speeder part. We can see the holes made for this purpose in the following figure. In addition, the screw will be attached to the engine by pressing fit. As we created a whole in the screw with the dimensions of the engine, it will be easy to carry it out successfully. It is shown below how the three elements look like after attaching them:

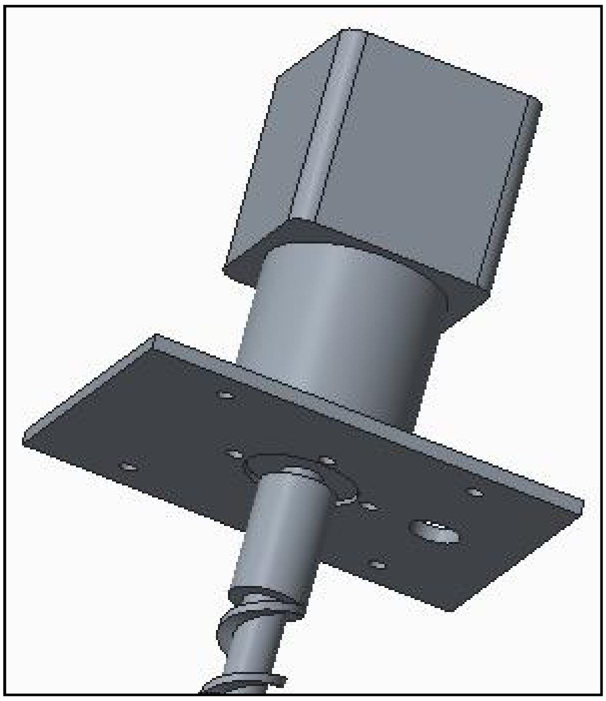

Figure 51. Screw and engine attachment.

In the other side, we have the rest of the elements belonging to the head's design. This part is more complex to be assembled, as there are many elements and most of them have to be attached in a specific order. The first step is to screw all the fans and all the resistors in order not to have to do it later, when everything will be assembled, so the spacing of maneuverability will be much smaller. The fans, both the layer ones and the ones to control the temperature of the material inside the cylinder, have four screws to be attached to the plates where they have to be placed. In the same way, the resistors need two screws to be joined to the heater pieces.

Once you have this prepared, the fixing plates can be introduced in their belonging position in the joints. Now, we have to assemble everything into the cylinder. We will begin threading the lower heater piece to the cylinder and the nozzle so then we have the three elements assemble to each other. After that, we will start introducing the elements in order throghout the cylinder from its upper part. So it will be in the following order: one of the joints with a fixing plate, the upper heater piece and the other joint with the fixing plate. We have to be sure that all the elements have the pretended orientation.

Finally we have to assemble the last elements. First, the plate where the layer fans are placed have to be attatched to the lower fixing plate. For it, we will use four threaded studs and its corresponding nuts, taking in to account the pretended orientation that we want. The last elements to be assembled are the joint and the hopper that will be just threaded in this order in the highest part of the cylinder. At this time we will have the two sides assembled and the only step missing in to screw one to the other by the four holes that the hopper and the plate where the material enters have. To place the head into the existing vertical plate in the 3D printer we will just have to screw the fixing plates to it, making holes located in the exact position for this, which will have been previously calculated.

All the elements and by extension the assembly have been designed in this way and not other for functionality purposes. Every element was designed to be the smallest, cheapest and easiest to be manufactured as possible. The pieces that should had been very similar to each other have been made exactly the same, so that we can create a production chain to save money and time.

9. Conclusion

After all this work in this challenging project, where we gave first an introduction to 3D world and then we focused our project in designing a new head that is able to print granulate plastic instead of filament, we come up with several conclusions.

As a general conclusion and after assessing the feasibility of the new design we can say that it is possible to implement the theoretical project. The calculations made and obtained for the different data sheets allow us to conclude that it is possible to obtain a 3D printer using granulate plastic as feeding material instead of the filament. Of couse, everything has been calculated in the ideal case so when implementing the redesign we will find some parameters that aren't as expected and we would have to change the dimensions of some elements to adjust these values to the pretended ones.

In addition, a couple of transformation process are necessary to be applied to the plastic before it is ready to enter in the extruder. As we have proposed during the memory, it will be necessary to subject the plastic to a drying process before been deposited in the hopper. Also, due to the small size of the extruder, the pellets must be transformed into powder. Using much smaller size granulates instead of pellets allows us to reduce the dimensions of the extruder, which is a huge advantage for our pretended goal of making it as small as possible and reduces also the head size because the rest of elements of it have a directly proportional relation.

The calculations presented in the memory are made with the idea of minimizing the size, and therefore the weight, of the extruder. The choice of diameter D = 15 mm and the relationship with the length L / D = 10 has been made because it was according with the machine in which we were going to attach the printer. Nevertheless, these dimensions are not the only solution and other configurations are possible and may be valid. For this reason, we have added the calculations for the other choices of diameter and lenght in the annexes.

Other aspect to be taken into account is that we have tried to maintain the maximum possible elements of the existing machine, so these elements such as the engine and the fans can be replaced from machine to machine.The other elements that do not exist in the market and have been designed by us. They have been designed trying to lighten the printer as much as possible while ensuring the proper operation of it. Another thing to be remarked is that the redesigned head just replace the existing one, maintaining the rest of the elements.

Finally, note that this project is just the first step of a larger project, and should continue with the construction of the elements, mount the printer, make the implementation of the electrics and electronics required system and the realization of the program that controls the motors, the temperatures and the speeds. In addition, the printer, once completed, should be tested to determine the correct parameters with which the machine works better as they may differ from those calculated above. For example, the air flow necessary to control the cylinder temperature cannot be calculated until the machine is tested.

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*Note: Webpages in Spanish.

11. Annexes

11.1. Parameters table

Screw parameters											
L/D	10	20	20	15	15	15	10	10	10	10	
Diameter (D)	15	15	20	10	15	20	10	15	20	10	mm
Lenght (L)	150	300	400	150	225	300	100	150	200	100	mm
Pitch (t)	15	15	20	10	15	20	10	15	20	10	mm
Helix angle (φ)	0,308050613	0,308050613	0,308050613	0,308050613	0,308050613	0,308050613	0,308050613	0,308050613	0,308050613	0,308050613	rad
Number of channels (m)	1	1	1	1	1	1	1	1	1	1	
Initial channel depth (h1)	3	3	4	2	3	4	2	3	4	2	mm
Ridge width (e)	1,8	1,8	2,4	1,2	1,8	2,4	1,2	1,8	2,4	1,2	mm
Filet clearance (δ)	0,03	0,03	0,04	0,02	0,03	0,04	0,02	0,03	0,04	0,02	mm
Final channel depth (h2)	1	1	1,333333333	0,666666667	1	1,333333333	0,666666667	1	1,333333333	0,666666667	mm
Compression relation (z)	3	3	3	3	3	3	3	3	3	3	
Feeding zone length	33	65	87	33	49	65	22	33	43	22	mm
Compression zone length	52	104	139	52	78	104	35	52	70	35	mm
Metering zone legnth	65	131	174	65	98	131	44	65	87	44	mm
Initial root radio (r)	4,50	4,50	6,00	3,00	4,50	6,00	3,00	4,50	6,00	3,00	mm
Final root radio (R)	6,50	6,50	8,67	4,33	6,50	8,67	4,33	6,50	8,67	4,33	mm

DICE PARAMETERS											
Initial conical zone diameter (d0)	15,06	15,06	20,08	10,04	15,06	20,08	10,04	15,06	20,08	10,04	mm
Conical zone diameter (d1)	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	mm
Cylindrical zone diameter (d2)	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	mm
Conical zone length (l1')	8	8	8	8	8	8	8	8	8	8	mm
Cylindrical length (l2')	2	2	2	2	2	2	2	2	2	2	mm
Conical zone constant(k1)	0,008635615	0,008635615	0,011592569	0,005678788	0,008635615	0,011592569	0,005678788	0,008635615	0,011592569	0,005678788	
Cylindrical zone cosntant (k2)	0,000314159	0,000314159	0,000314159	0,000314159	0,000314159	0,000314159	0,000314159	0,000314159	0,000314159	0,000314159	
Geometrical constant (k)	0,000303131	0,000303131	0,00030587	0,000297691	0,000303131	0,00030587	0,000297691	0,000303131	0,00030587	0,000297691	

11.2. Screw weight table

L/D	10	20	20	15	15	15	10	10	10	10	
Diameter (D)	15	15	20	10	15	20	10	15	20	10	mm
Feeding zone lenght	33	65	87	33	49	65	22	33	43	22	mm
Compression zone lenght	52	104	139	52	78	104	35	52	70	35	mm
Metering zone lenght	65	131	174	65	98	131	44	65	87	44	mm
Filets in feeding zone	2,2	4,3	4,3	3,3	3,3	3,3	2,2	2,2	2,2	2,2	
Filets in compression zone	3,5	7,0	7,0	5,2	5,2	5,2	3,5	3,5	3,5	3,5	
Filets in metering zone	4,4	8,7	8,7	6,5	6,5	6,5	4,4	4,4	4,4	4,4	
Filet lenght	49,4536246	49,4536246	65,9381662	32,9690831	49,4536246	65,9381662	32,9690831	49,4536246	65,9381662	32,9690831	mm
Feeding zone root volume	2070,74153	4141,48306	9816,84872	920,329568	3106,11229	7362,63654	613,553045	2070,74153	4908,42436	613,553045	mm^3
Compression zone root volume	5015,39559	10030,7912	23776,6902	2229,06471	7523,09339	17832,5177	1486,04314	5015,39559	11888,3451	1486,04314	mm^3
Metering zone root volume	8660,7819	17321,5638	41058,5216	3849,2364	12991,1728	30793,8912	2566,1576	8660,7819	20529,2608	2566,1576	mm^3
Feeding zone filet volume	579,497574	1158,99515	2747,24776	257,554477	869,24636	2060,43582	171,702985	579,497574	1373,62388	171,702985	mm^3
Compression zone filet volume	619,55501	1239,11002	2937,14967	275,357782	929,332514	2202,86226	183,571855	619,55501	1468,57484	183,571855	mm^3
Metering zone filet volume	387,221881	774,443762	1835,71855	172,098614	580,832821	1376,78891	114,732409	387,221881	917,859273	114,732409	mm^3
Root total volume	15746,919	31493,838	74652,0605	6998,63067	23620,3785	55989,0454	4665,75378	15746,919	37326,0303	4665,75378	mm^3
Filets total volume	1586,27446	3172,54893	7520,11598	705,010873	2379,4117	5640,08698	470,007249	1586,27446	3760,05799	470,007249	mm^3
Unthreaded part volume	3663,88243	3663,88243	3663,88243	3663,88243	3663,88243	3663,88243	3663,88243	3663,88243	3663,88243	3663,88243	mm^3
Total volume	20997,0759	38330,2694	85836,0589	11367,524	29663,6727	65293,0148	8799,64346	20997,0759	44749,9707	8799,64346	mm^3
Density	7700										
Mass	0,16167748	0,29514307	0,66093765	0,08752993	0,22841028	0,50275621	0,06775725	0,16167748	0,34457477	0,06775725	kg

11.3. Operating parameters

Screw parameters											
L/D	10	20	20	15	15	15	10	10	10	10	
Diameter (D)	15	15	20	10	15	20	10	15	20	10	mm
FLOW RATE											
Flow (Q)	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	4,67E+00	mm^3/seg
Drag flow (α)	847,2763299	847,2763299	2008,358708	251,0448385	847,2763299	2008,358708	251,0448385	847,2763299	2008,358708	251,0448385	mm^3
Pressure flow (β)	0,057207905	0,028603952	0,067801961	0,011300327	0,038138603	0,090402615	0,01695049	0,057207905	0,135603923	0,01695049	mm^3
Filtration flow (Y)	7,06569E-06	3,53284E-06	8,37415E-06	1,39569E-06	4,71046E-06	1,11655E-05	2,09354E-06	7,06569E-06	1,67483E-05	2,09354E-06	mm^3
Dice constant (K)	0,000303131	0,000303131	0,00030587	0,000297691	0,000303131	0,00030587	0,000297691	0,000303131	0,00030587	0,000297691	mm^3
Output speed (v)	37,12289048	37,12289048	37,12289048	37,12289048	37,12289048	37,12289048	37,12289048	37,12289048	37,12289048	37,12289048	mm/s
Angular velocity (η)	62,5	31,50678712	31,03665744	43,44327395	41,89893194	41,33575408	64,60744079	62,68322158	61,93394735	64,60744079	rpm
Shear rate (υ)	100	100	1000	100	100	100	100	100	100	100	s^-1
Effective viscosity (u)	650	650	650	650	650	650	650	650	650	650	Pa·s
Density (ρ)	1,30E-06	1,30E-06	1,30E-06	1,30E-06	1,30E-06	1,30E-06	1,30E-06	1,30E-06	1,30E-06	1,30E-06	kg/mm^3
Mass flow (m)	6,06E-06	6,06E-06	6,06E-06	6,06E-06	6,06E-06	6,06E-06	6,06E-06	6,06E-06	6,06E-06	6,06E-06	kg/min
pressure (Pmax)	1,00E+07	1,01E+07	9,96E+06	1,05E+07	1,01E+07	9,95E+06	1,04E+07	1,01E+07	9,94E+06	1,04E+07	pa
Requiered power (N)	3,72E+02	3,72E+02	3,72E+02	3,72E+02	3,72E+02	3,72E+02	3,72E+02	3,72E+02	3,72E+02	3,72E+02	W
HEATER POWER											
Heat constant (k)	1386	1386	1386	1386	1386	1386	1386	1386	1386	1386	J/(kg·K)
Temperature variation (Tm-T0)	180	180	180	180	180	180	180	180	180	180	K
Heat bed power	2,52E-02	2,52E-02	2,52E-02	2,52E-02	2,52E-02	2,52E-02	2,52E-02	2,52E-02	2,52E-02	2,52E-02	W

NOTE: all the parameters had been calculated for different combinations of diameters and relations between the lenght and the diameter, so it can be seen not only the parameters for the choosen ones but also the other possible option parameters.

11.4. Datasheets

11.4.1. Engine datasheet

1.8° NEMA 17 GEARED STEPPER MOTOR WITH PLANETARY GEARBOX

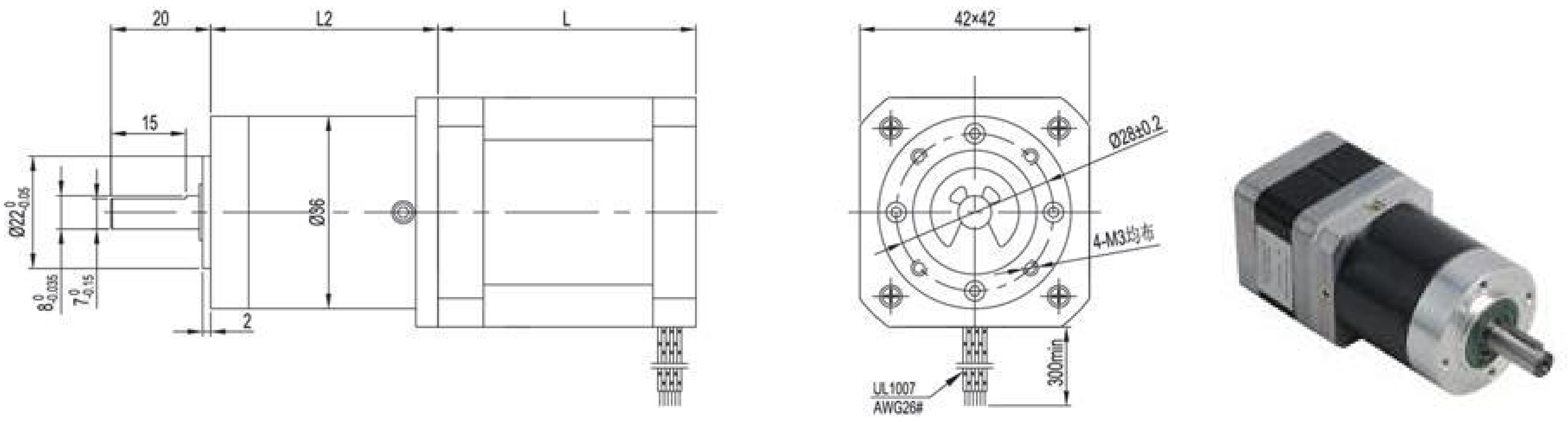
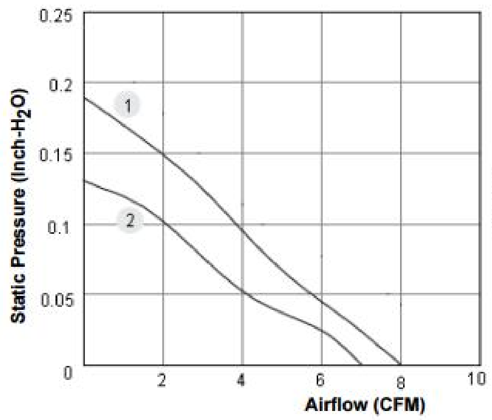


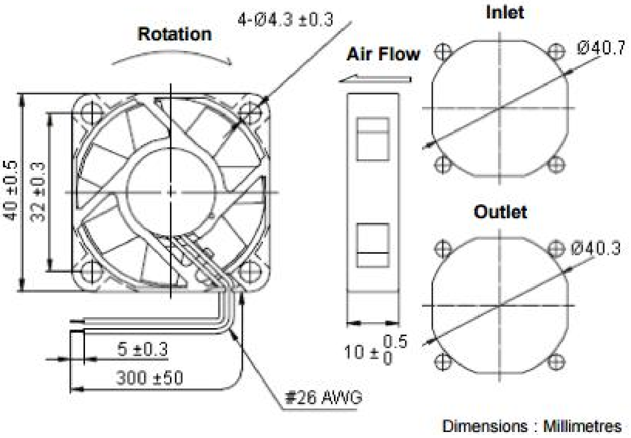
TABLE 1. MOTOR SPECIFICATIONS									
Model	Length L	Rated Current	Resistance	Inductance	Holding Torque	Holding Torque	Rotor Interia	Lead wires	Weight
	mm	A	Ω/Phase	mH/Phase	Oz.in	N.m	g.cm2		g
42HS20-0804Z	20	0.8	3.8	4.5	14.2	0.1	24	4	120
42HS28-0604Z	28	0.6	8	10	17	0.12	30	4	150
42HS34-1304Z	34	1.3	2.4	2.8	40	0.28	34	4	220
42HS34-0406Z	34	0.4	30	18	40	0.28	34	6	220
42HS40-1304Z	40	1.3	2.5	5	57	0.4	54	4	280
42HS40-1704Z	40	1.7	1.5	2.8	57	0.4	54	4	280
42HS48-1304Z	48	1.3	3.2	5.5	74	0.52	68	4	350
42HS48-1704Z	48	1.7	1.8	3.2	74	0.52	68	4	350
42HS60-1704Z	60	1.7	2.3	4.6	100	0.7	80	4	480
42HS60-2304Z	60	2.3	1.4	2.5	100	0.7	80	4	480

TABLE 2. GEARBOX SPECIFICATIONS					
Model		36PLGB1-xxZ	36PLGB2-xxZ	36PLGB3-xxZ	36PLGB4-xxZ
Number of gear trains		1	2	3	4
Gear ratio		3.7, 5.2	14, 19, 27	51, 71, 100, 139	189, 264, 369
Length L2	mm	31	38.5	48.4	55.8
Rated output torque	N.m	0.3	1	2	3
Max output torque	N.m	0.9	3	6	9
Efficiency	%	9	81	73	66
Weight	g	191	207	288	312

11.4.2. Fan datasheet

MULTICOMP MC36257 Axial Fan, Brushless Motor, Tubeaxial, Sleeve, 12 VDC, 40 mm, 10 mm, 7 cu.ft/min, 0.226 m³/min





- **Supply Voltage** 12VDC
- **Fan Frame Size** 40mm
- **External Depth** 10mm
- **Flow Rate - Imperial** 7cu.ft/min
- **Flow Rate - Metric** 0.226m³/min
- **Noise Rating** 27dBA
- **Bearing Type** Sleeve
- **Power Connection Type** Wire Leaded
- **Frame Dimensions** 40mm x 40mm x 10mm
- **External Width** 40 mm
- **Current Type** DC
- **Current Rating** 90 mA

11.4.3. Resistor datasheet

Wirewound Resistors, Military, MIL-PRF-18546 Qualified, Type RE, Aluminum Housed, Chassis Mount

FEATURES

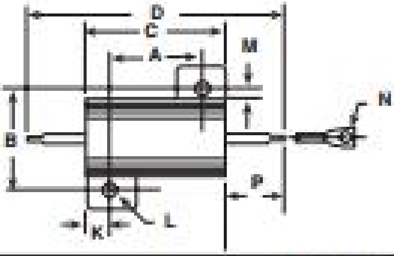
- Molded construction for total environmental protection
- Complete welded construction
- Meets applicable requirements of MIL-PRF-18546
- Available in non-inductive styles (type NH) with Aryton-Perry winding for lowest reactive components
- Mounts on chassis to utilize heat-sink effect
- Excellent stability in operation

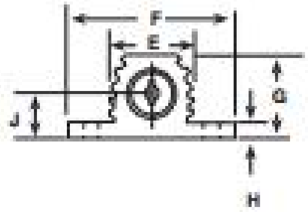
STANDARD ELECTRICAL SPECIFICATIONS

MODEL	MIL-PRF-18546 TYPE	POWER RATING $P_{25°C}$ W		RESISTANCE RANGE MIL. RANGE SHOWN IN BOLD FACE Ω				WEIGHT (Typical)
		DALE	MILITARY	±0.05%, ±0.1%	±0.25%	±0.5%	±1%, ±3%, ±5%	g
RH-5	— RE60G	7.5 (5)	5	0.5 - 6.75k —	0.1 - 8.6k —	0.05 - 8.6k —	0.02 - 24.5k 0.10 - 3.32k	3
NH-5	— RE60N	7.5 (5)	5	0.5 - 2.32k —	0.1 - 3.27k —	0.05 - 3.27k —	0.05 - 12.75k 1.0 - 1.65k	3.3
RH-10	— RE65G	12.5 (10)	10	0.5 - 12.7k —	0.1 - 16.69k —	0.05 - 16.69k —	0.01 - 47.1k 0.10 - 5.62k	6
NH-10	— RE65N	12.5 (10)	10	0.5 - 4.45k —	0.1 - 5.54k —	0.05 - 5.54k —	0.05 - 23.5k 1.0 - 2.8k	8.8
RH-25	— RE70G	25	20	0.5 - 25.7k —	0.1 - 32.99k —	0.05 - 32.99k —	0.01 - 95.2k 0.10 - 12.1k	13
NH-25	— RE70N	25	20	0.5 - 9.09k —	0.1 - 12.8k —	0.05 - 12.8k —	0.05 - 47.6k 1.0 - 6.04k	16.5
RH-50	— RE75G	50	30	0.5 - 73.4k —	0.1 - 96k —	0.05 - 96k —	0.01 - 273k 0 .10 - 39.2k	28
NH-50	— RE75N	50	30	0.5 - 26k —	0.1 - 36.7k —	0.05 - 36.7k —	0.05 - 136k 1.0 - 19.6k	35
RH-100	— RE77G	100	75	0.5 - 90k —	0.1 - 90k —	0.05 - 90k —	0.05 - 90k 0.05 - 29.4k	350
NH-100	— RE77N	100	75	0.5 - 37.5k —	0.1 - 37.5k —	0.05 - 37.5k —	0.05 - 37.5k 1.0 - 14.7k	385
RH-250	— RE80G	250	120	0.5 - 116k —	0.1 - 116k —	0.05 - 116k —	0.05 - 116k 0.10 - 35.7k	630
NH-250	— RE80N	250	120	0.5 - 48.5k —	0.1 - 48.5k —	0.05 - 48.5k —	0.05 - 48.5k 1.0 - 17.4k	690

DIMENSIONS

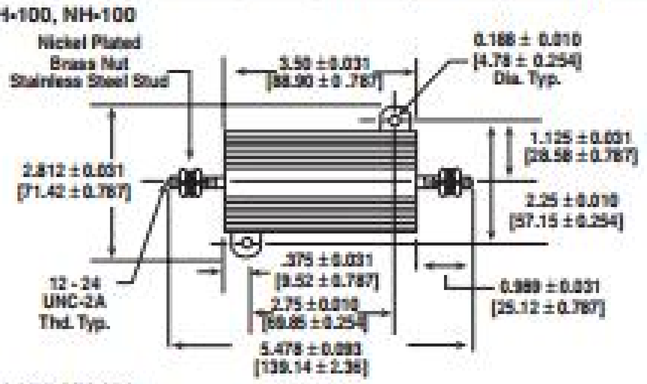
RH-5, -10, -25, -50
NH-5, -10, -25, -50

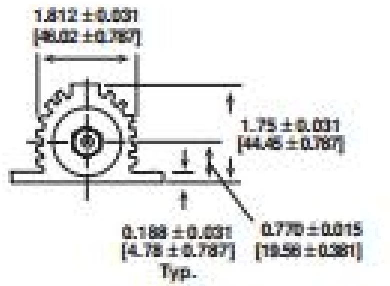




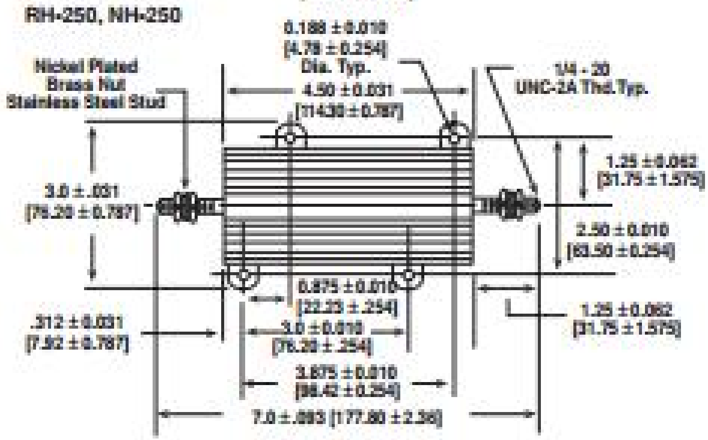
MODEL	DIMENSIONS in inches [millimeters]													
	A	B	C	D	E	F	G	H	J	K	L	M	N	P
RH-5 NH-5	0.444 ± 0.005 [11.28 ± 0.127]	0.490 ± 0.005 [12.45 ± 0.127]	0.600 ± 0.031 [15.24 ± 0.787]	1.125 ± 0.062 [28.58 ± 1.57]	0.334 ± 0.015 [8.48 ± 0.381]	0.646 ± 0.015 [16.41 ± .381]	0.320 ± 0.015 [8.13 ± 0.381]	0.065 ± 0.010 [1.65 ± 0.254]	0.133 ± 0.010 [3.38 ± 0.254]	0.078 ± 0.010 [1.98 ± 0.254]	0.093 ± 0.005 [2.36 ± 0.127]	0.078 ± 0.015 [1.98 ± .381]	0.050 ± 0.005 [1.27 ± 0.127]	0.266 ± 0.062 [6.76 ± 1.57]
RH-10 NH-10	0.562 ± 0.005 [14.27 ± 0.127]	0.625 ± 0.005 [15.88 ± 0.127]	0.750 ± 0.031 [19.05 ± 0.787]	1.375 ± 0.062 [34.93 ± 1.57]	0.420 ± 0.015 [10.67 ± 0.381]	0.800 ± 0.015 [20.32 ± 0.381]	0.390 ± 0.015 [9.91 ± 0.381]	0.075 ± 0.010 [1.91 ± 0.254]	0.165 ± 0.010 [4.19 ± 0.254]	0.093 ± 0.010 [2.36 ± 0.254]	0.094 ± 0.005 [2.39 ± 0.127]	0.102 ± 0.015 [2.59 ± 0.381]	0.085 ± 0.005 [2.16 ± 0.127]	0.312 ± 0.062 [7.92 ± 1.57]
RH-25 NH-25	0.719 ± 0.005 [18.26 ± 0.127]	0.781 ± 0.005 [19.84 ± 0.127]	1.062 ± 0.031 [26.97 ± 0.787]	1.938 ± 0.062 [49.23 ± 1.57]	0.550 ± 0.015 [13.97 ± .381]	1.080 ± 0.015 [27.43 ± 0.381]	0.546 ± 0.015 [13.87 ± 0.381]	0.075 ± 0.010 [1.91 ± 0.254]	0.231 ± 0.010 [5.87 ± 0.254]	0.172 ± 0.010 [4.37 ± 0.254]	0.125 ± 0.005 [3.18 ± 0.127]	0.115 ± 0.015 [2.92 ± 0.381]	0.085 ± 0.005 [2.16 ± 0.127]	0.438 ± 0.062 [11.13 ± 1.57]
RH-50 NH-50	1.562 ± 0.005 [39.67 ± 0.127]	0.844 ± 0.005 [21.44 ± 0.127]	1.968 ± 0.031 [49.99 ± 0.787]	2.781 ± 0.062 [70.64 ± 1.57]	0.630 ± 0.015 [16.00 ± 0.381]	1.140 ± 0.015 [28.96 ± 0.381]	0.610 ± 0.015 [15.49 ± 0.381]	0.088 ± 0.010 [2.24 ± 0.254]	0.260 ± 0.010 [6.60 ± 0.254]	0.196 ± 0.010 [4.98 ± 0.254]	0.125 ± 0.005 [3.18 ± 0.127]	0.107 ± 0.015 [2.72 ± 0.381]	0.085 ± 0.005 [2.16 ± 0.127]	0.438 ± 0.062 [11.13 ± 1.57]

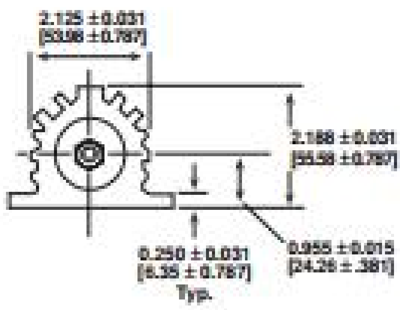
RH-100, NH-100





RH-250, NH-250





TECHNICAL SPECIFICATIONS

PARAMETER	UNIT	RH RESISTOR CHARACTERISTICS
Temperature Coefficient	ppm/°C	± 100 for 0.1Ω to 0.99Ω, ± 50 for 1Ω to 9.9Ω, ± 20 for 10Ω and above
Dielectric Withstanding Voltage	V_{AC}	1000 for RH-5, RH-10 and RH-25, 2000 for RH-50, 4500 for RH-100 and RH-250
Short Time Overload	-	5 x rated power for 5 seconds
Maximum Working Voltage	V	$(P \times R)^{1/2}$
Insulation Resistance	Ω	10,000 Megohm minimum dry, 1000 Megohm minimum after moisture test
Terminal Strength	lb	5 minimum for RH-5 and RH-10, 10 minimum for all others
Solderability	-	MIL-PRF-18546 Type - Meets requirements of ANSI J-STD-002
OperatingTemperature Range	°C	- 55/+ 250

POWER RATING

Vishay RH resistor wattage ratings are based on mounting to the following heat sink:

RH-5 and RH-10:	4" x 6" x 2" x 0.040" thick aluminum chassis (129 sq. in. surface area)
RH-25:	5" x 7" x 2" x 0.040" thick aluminum chassis (167 sq. in. surface area)
RH-50:	12" x 12" x 0.059" thick aluminum panel (291 sq. in. surface area)
RH-100 and RH-250:	12" x 12" x 0.125" thick aluminum panel (294 sq. in. surface area)

AMBIENT TEMPERATURE DERATING

Derating is required for ambient temperatures above 25°C, see the following graph.

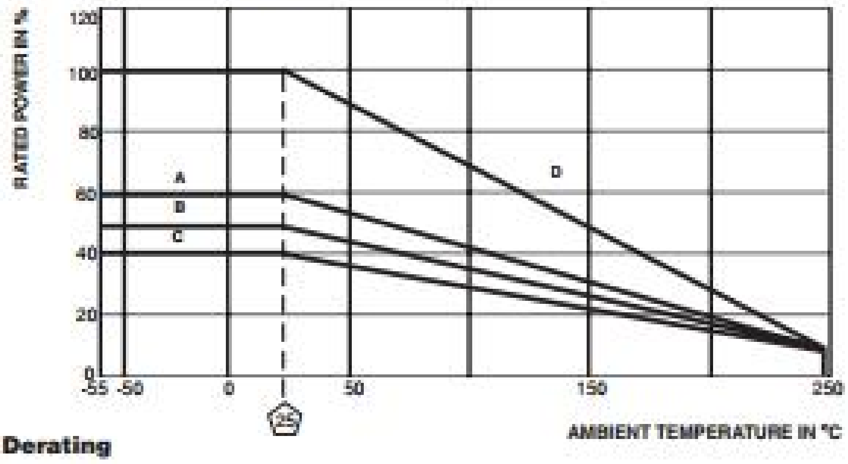
Curves A, B, C apply to operation of unmounted resistors. Curve D applies to all types when mounted to specified heat sink.

A = RH-5 and RH-10 size resistor, unmounted

B = RH-25 size resistor, unmounted

C = RH-50, RH-100 and RH-250 size resistor, unmounted

D = All types mounted to recommended aluminum heat sink



Derating

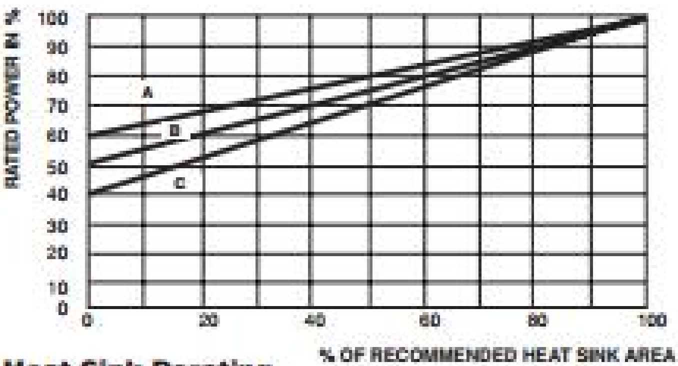
REDUCED HEAT SINK DERATING:

Derating is also required when recommended heat sink area is reduced.

A = RH-5 and RH-10 size resistor

B = RH-25 size resistor

C = RH-50, RH-100 and RH-250 size resistor



Heat Sink Derating

MATERIAL SPECIFICATIONS

Element: Copper-nickel alloy or nickel-chrome alloy, depending on resistance value

Core: Ceramic, steatite or alumina, depending on physical size

Encapsulant: Silicone molded construction

Housing: Aluminum with hard anodic coating

End Caps: Stainless steel

Standard Terminals: Tinned Copperweld® on RH-5 through RH-50 size, threaded stainless steel terminals on RH-100 and RH-250

Part Marking: DALE, Model, Wattage, Value, Tolerance, Date Code

NH NON-INDUCTIVE

Models of equivalent physical and electrical specifications are available with non-inductive (Aryton-Perry) winding. They are identified by substituting the letter N for R in the model number (NH-5, for example).

SPECIAL MODIFICATIONS

A number of special modifications to the aluminum housed resistor style are available upon request. Special modifications include:

- Terminal configurations and materials
- Resistance values and tolerances
- Low resistance temperature coefficient (RTC)
- Housing configuration
- Threaded mounting holes
- Preconditioning and other additional testing

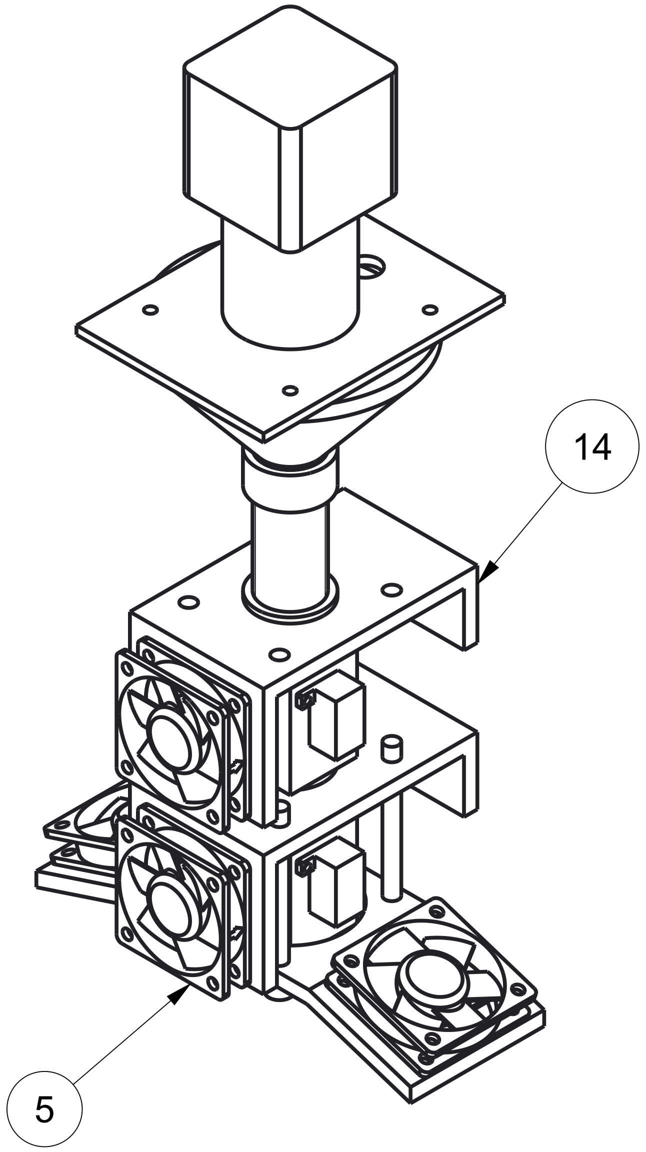
APPLICABLE MIL SPECIFICATIONS

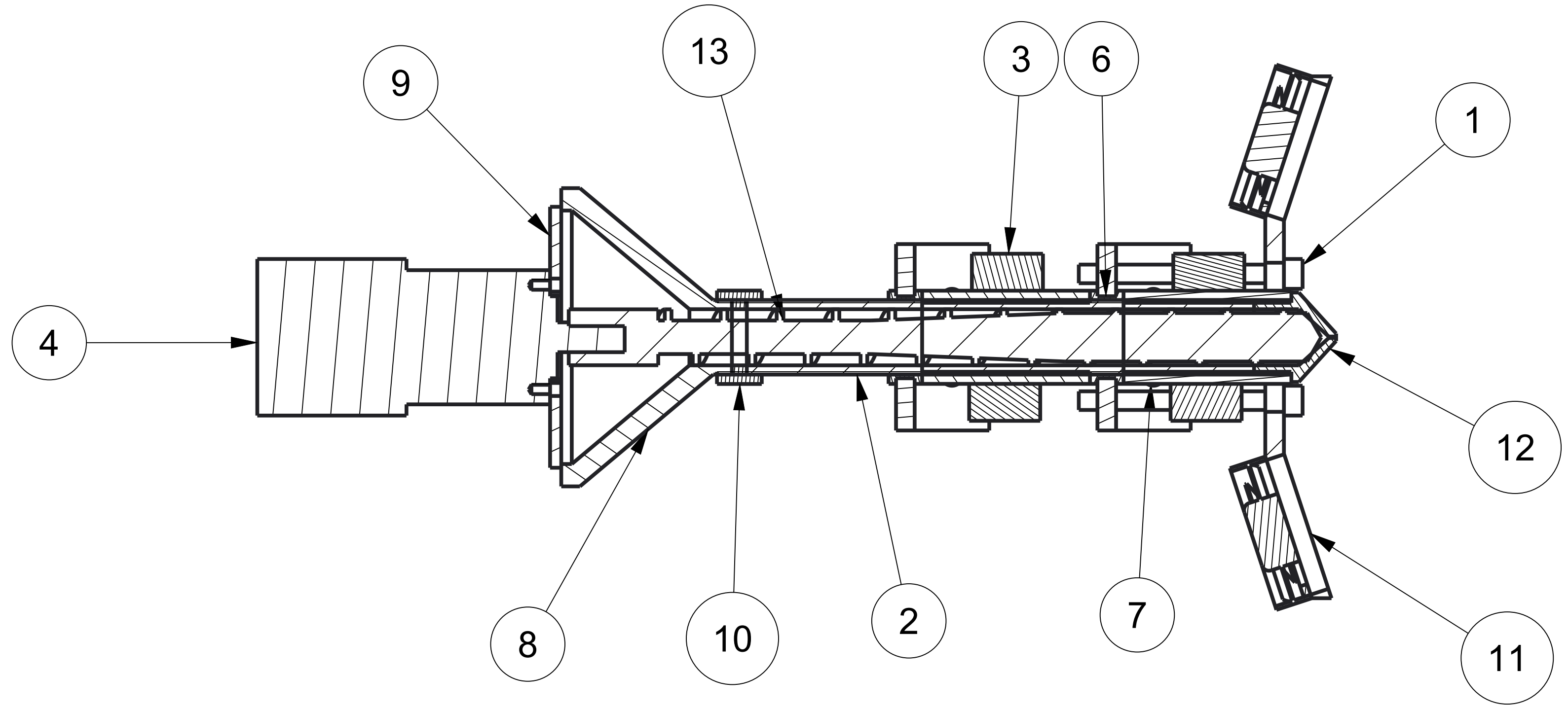
MIL-PRF-18546 is the military specification covering aluminum housed, chassis mount, power resistors. VISHAY RH and NH resistors are listed as qualified on the MIL-PRF-18546 QPL.

PERFORMANCE

TEST	CONDITIONS OF TEST	TEST LIMITS
Thermal Shock	Rated power applied until thermally stable, then a minimum of 15 minutes at - 55°C	± (0.5% + 0.05Ω) ΔR
Short Time Overload	5 x rated power for 5 seconds	± (0.5% + 0.05Ω) ΔR
Dielectric Withstanding Voltage	1000Vrms for RH-5, RH-10 and RH-25; 2000Vrms for RH-50 4500Vrms for RH-100 and RH-250; duration one minute	± (0.2% + 0.05Ω) ΔR
Temperature	250°C for 2 hours	± (0.5% + 0.05Ω) ΔR
Moisture Resistance	MIL-STD-202 Method 106, 7b not applicable	± (1.0% + 0.05Ω) ΔR
Shock, Specified Pulse	MIL-STD-202 Method 213, 100g's for 6 milliseconds, 10 shocks	± (0.2% + 0.05Ω) ΔR
Vibration, High Frequency	Frequency varied 10 to 2000Hz, 20g peak, 2 directions 6 hours each	± (0.2% + 0.05Ω) ΔR
Load Life	1000 hours at rated power, + 25°C, 1.5 hours "ON", 0.5 hours "OFF"	± (1.0% + 0.05Ω) ΔR
Terminal Strength	30 second, 5 pound pull test for RH-5 and RH-10, 10 pound pull test for other sizes, torque test - 24 pound inch for RH-100 and 32 pound inch for RH-250	± (0.2% + 0.05Ω) ΔR

11.5. Drawings

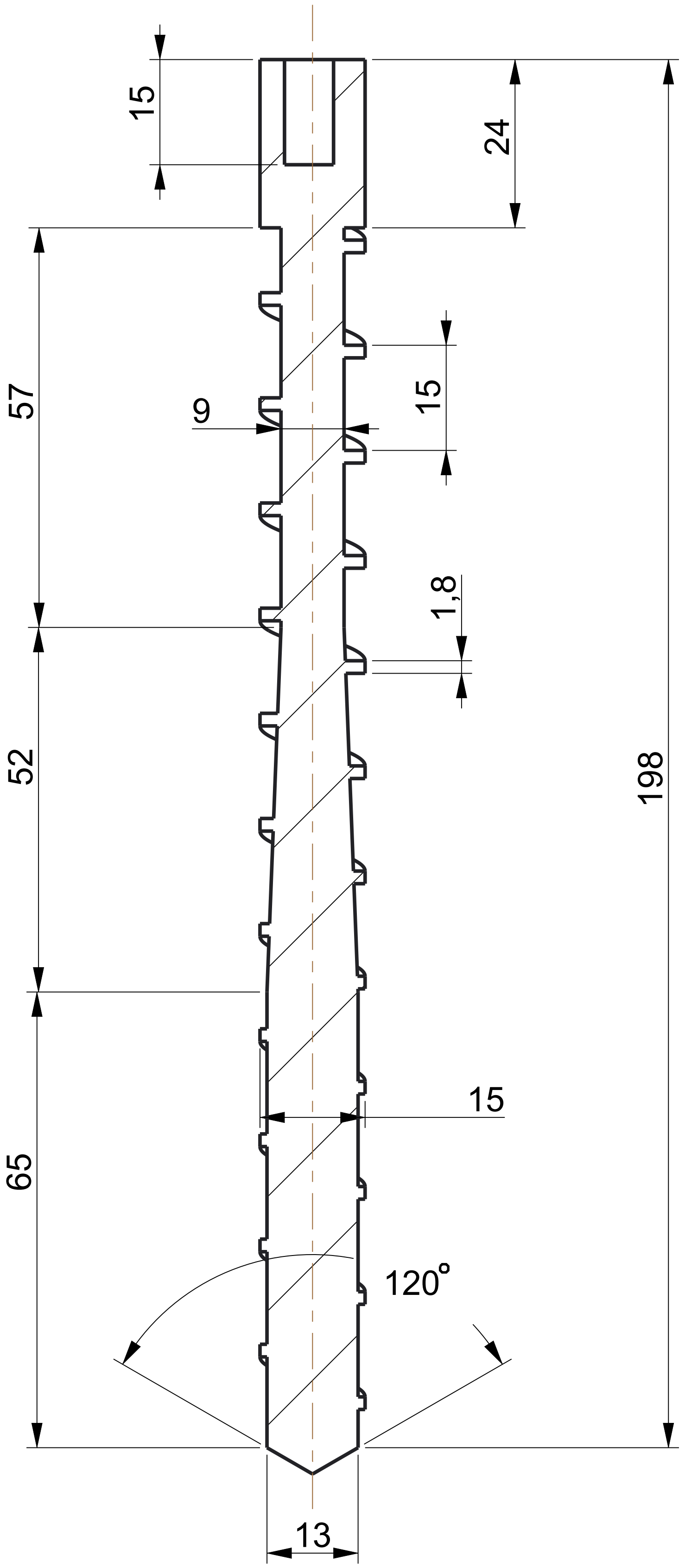


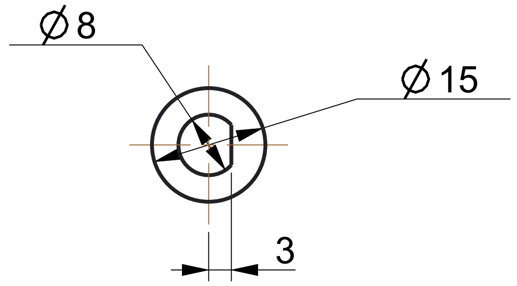


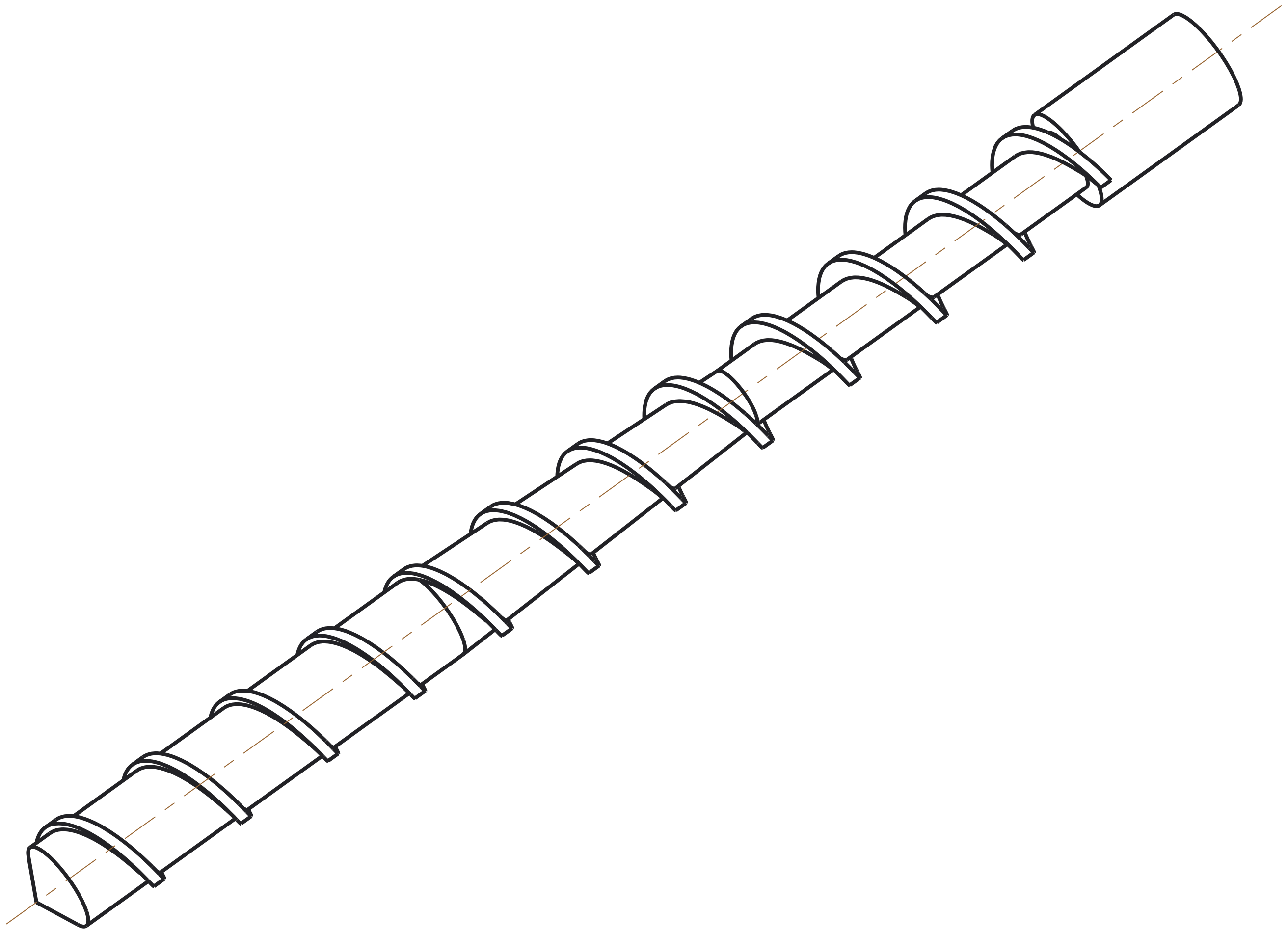
ITEM NUMBER	NAME	NUMBER OF ITEMS	DESCRIPTION	MATERIAL
14	SUPPORT	2		ALUMINIUM
13	SCREW	1		STEEL F-174
12	NOZZLE	1		BRASS
11	LAYER_FAN_SUPPORT	1		PLA
10	JOINT	1		TEFLON
9	HOPPER_PLATE	1		ALUMINIUM
8	HOPPER	1		CORZAN
7	HEATER	2		ALUMINIUM
6	FIXING_JOINT	2		TEFLON
5	FAN	4	MULTICOMP MC36257	
4	ENGINE	1	NEMA17 42HS40-1704Z 36PLGB2-xxZ	
3	ELECTRIC_RESISTANCE	4	RH10 RE65G	
2	CYLINDER	1		STEEL F-174
1	BOLT	4		STEEL

ISO-symbool	katholieke hogeschool vives associatie KU Leuven	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model	
			Tekening	ASSEMBLY 31/05/2016
			Gezien	
Schaal: 1:2	ARTURO BAHILLO RUIZ		Blad: 1 12	
		Model: EXTRUDER_ASSEMBLY	DWG: ASSEMBLY	A3

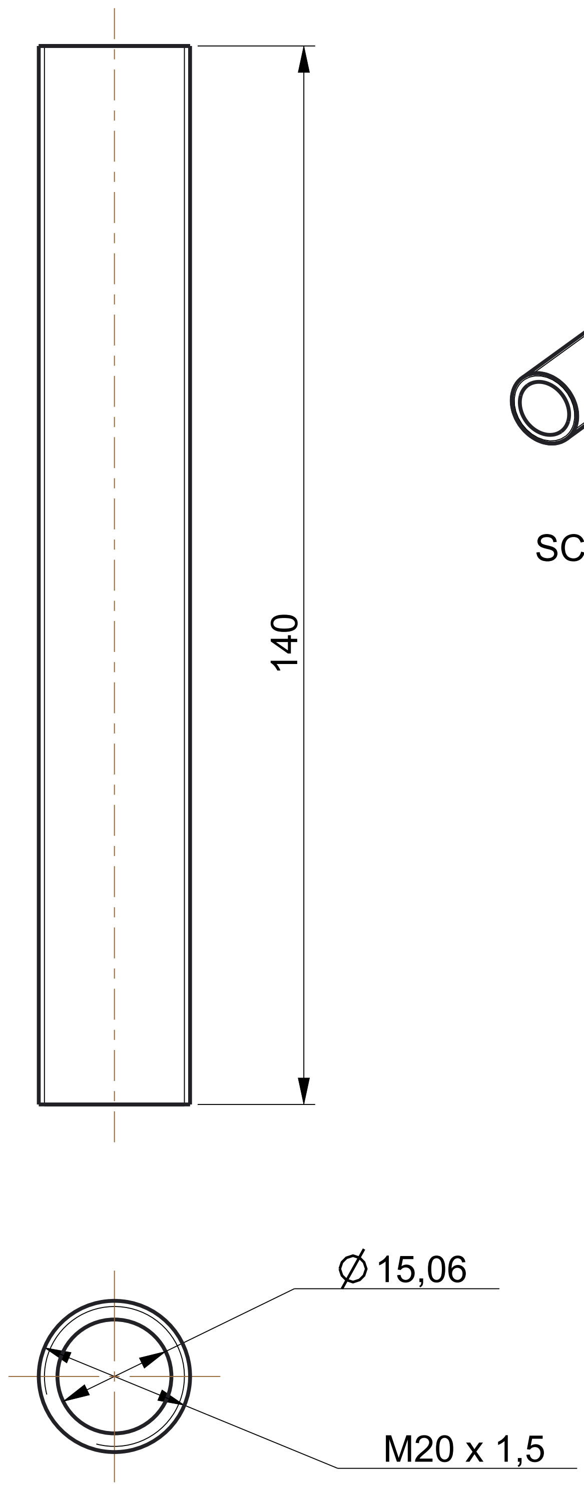
SECTION A-A

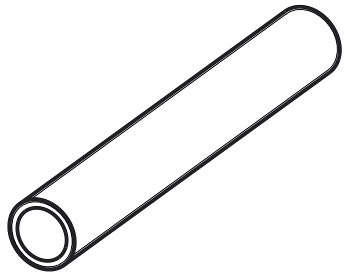






ISO-symbool	katholieke hogeschool associatie KU Leuven vives Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model	
		Tekening	SCREW 02/06/2016
		Gezien	
Schaal: 1:1	ARTURO BAHILLO RUIZ	Model: SCREW	DWG: SCREW_
Blad: 2 12			A3



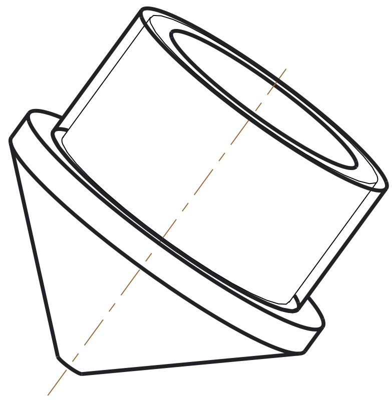


SCALE 1: 2

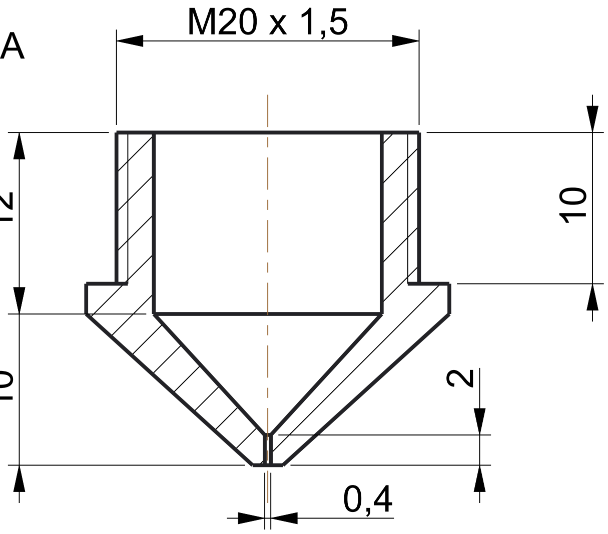
ISO-symbool	katholieke hogeschool vives associatie KU Leuven	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
			Tekening	CYLINDER	31/05/2016
			Gezien		

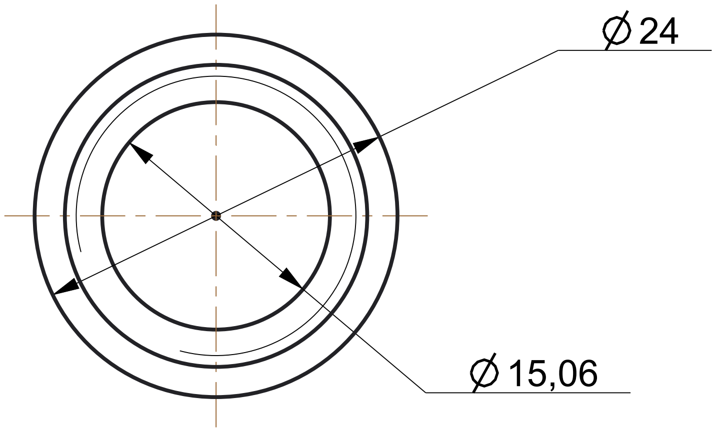
Schaal: 1:1	ARTURO BAHILLO RUIZ	Blad: 3 / 12
	Model: BARREL	DWG: CYLINDER

A4



SECTION A-A

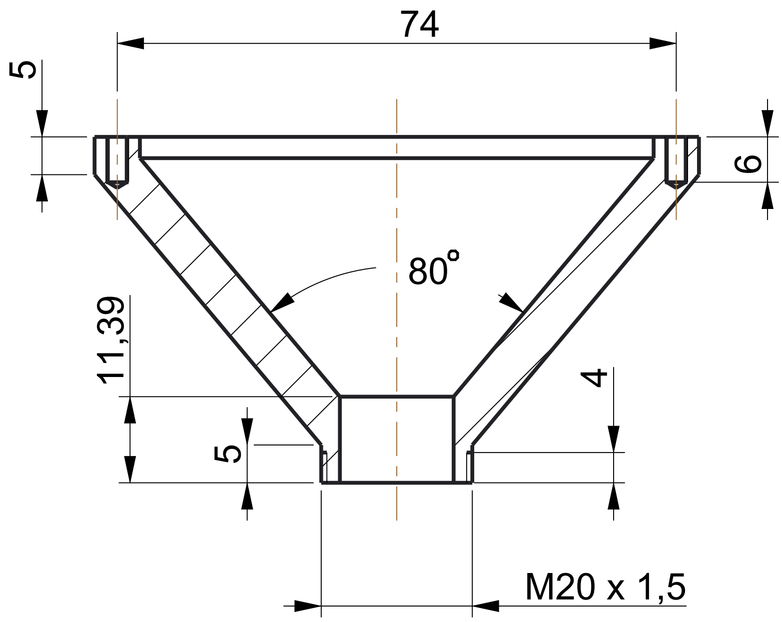


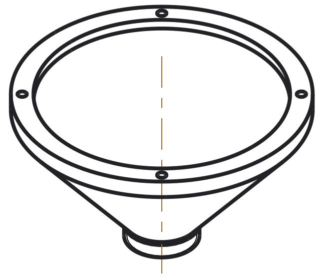


ISO-symbool	katholieke hogeschool associatie KU Leuven vives	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
			Tekening	NOZZLE	31/05/2016
			Gezien		
Schaal: 2:1	ARTURO BAHILLO RUIZ		Model: DIE	DWG: NOZZLE	Blad: 4 / 12

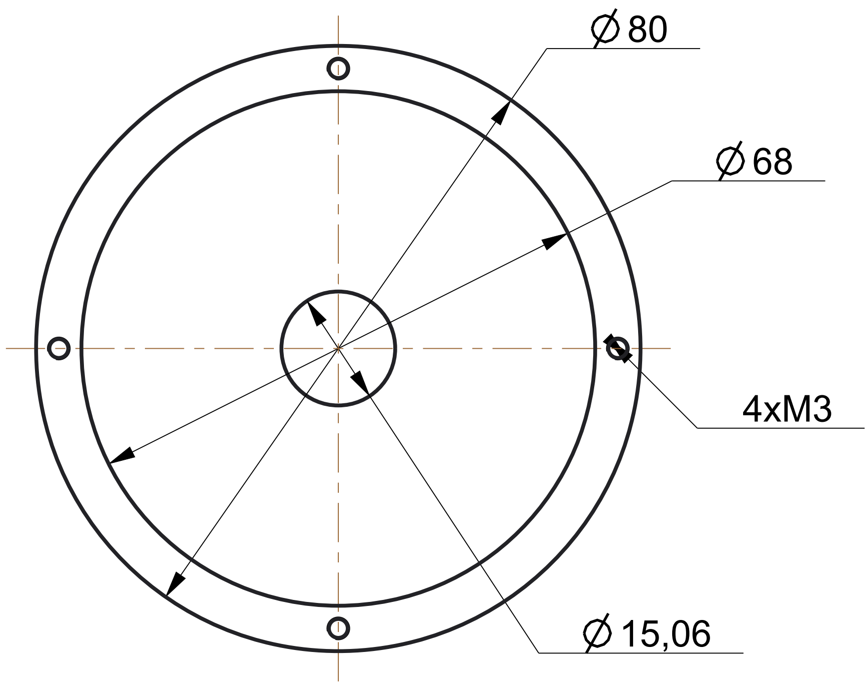
A4

SECTION A-A



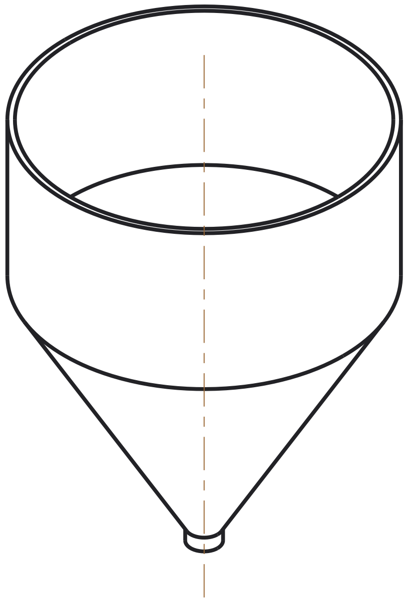


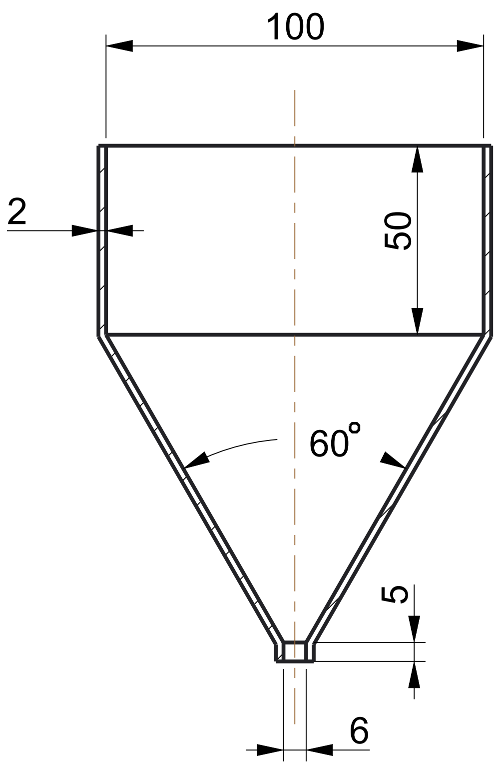
SCALE 1:2



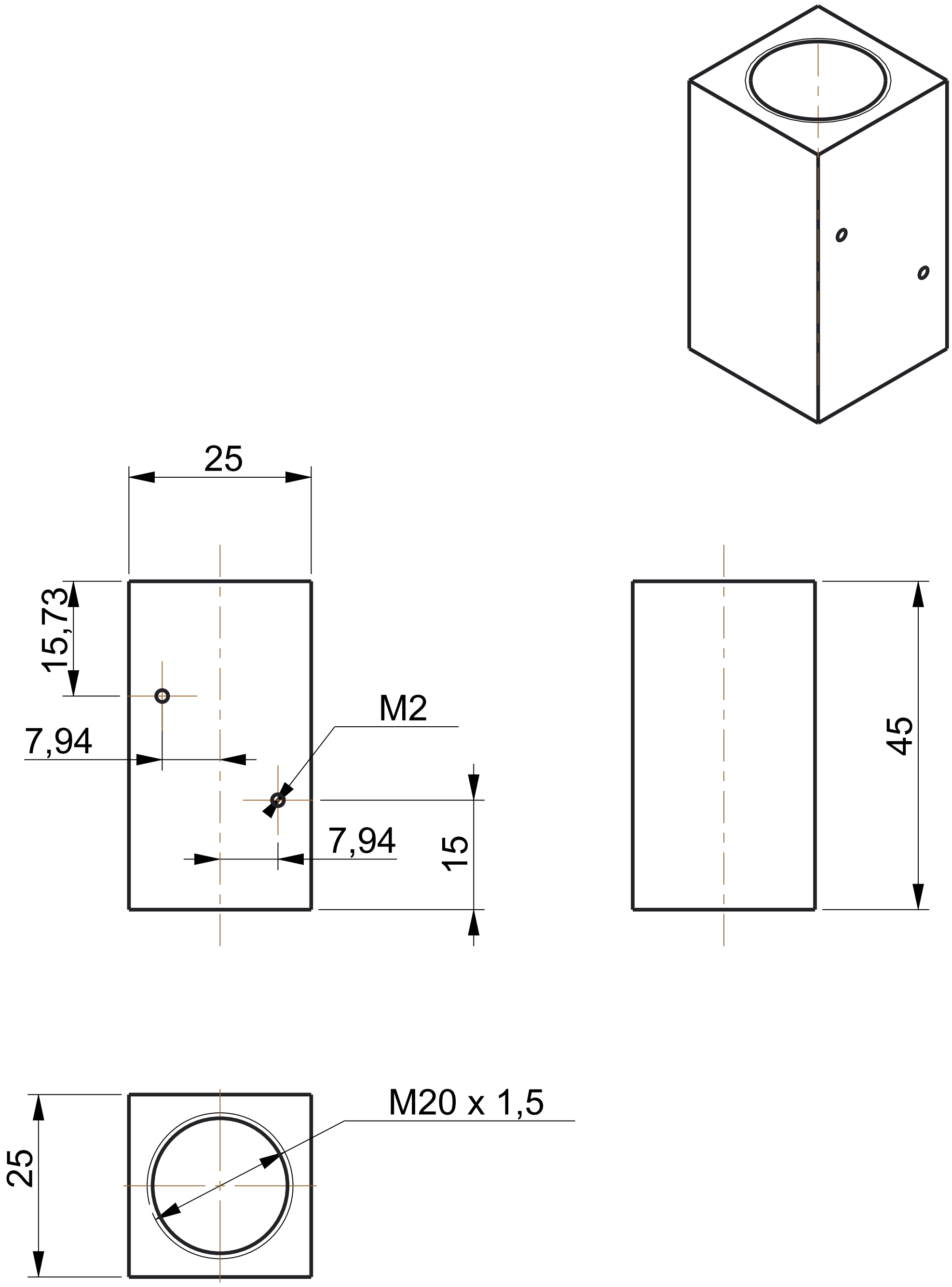
ISO-symbool	katholieke hogeschool associatie KU Leuven vives Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
		Tekening	LOWER HOPPER	31/05/2016
		Gezien		
Schaal: 1:1	ARTURO BAHILLO RUIZ	Model: HOPPER	DWG: LOWER_HOPPER	Blad: 5 12

A4





ISO-symbool	katholieke hogeschool vives associatie KU Leuven	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	
Model			
Tekening	UPPER HOPPER	31/05/2016	
Gezien			
Schaal: 1:2	ARTURO BAHILLO RUIZ	Blad: 6	12
	Model: UPPER_HOPPER	DWG: UPPER_HOPPER	A4



ISO-symbool	katholieke hogeschool vives associatie KU Leuven Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
		Tekening	HEATER PIECE	31/05/2016
		Gezien		

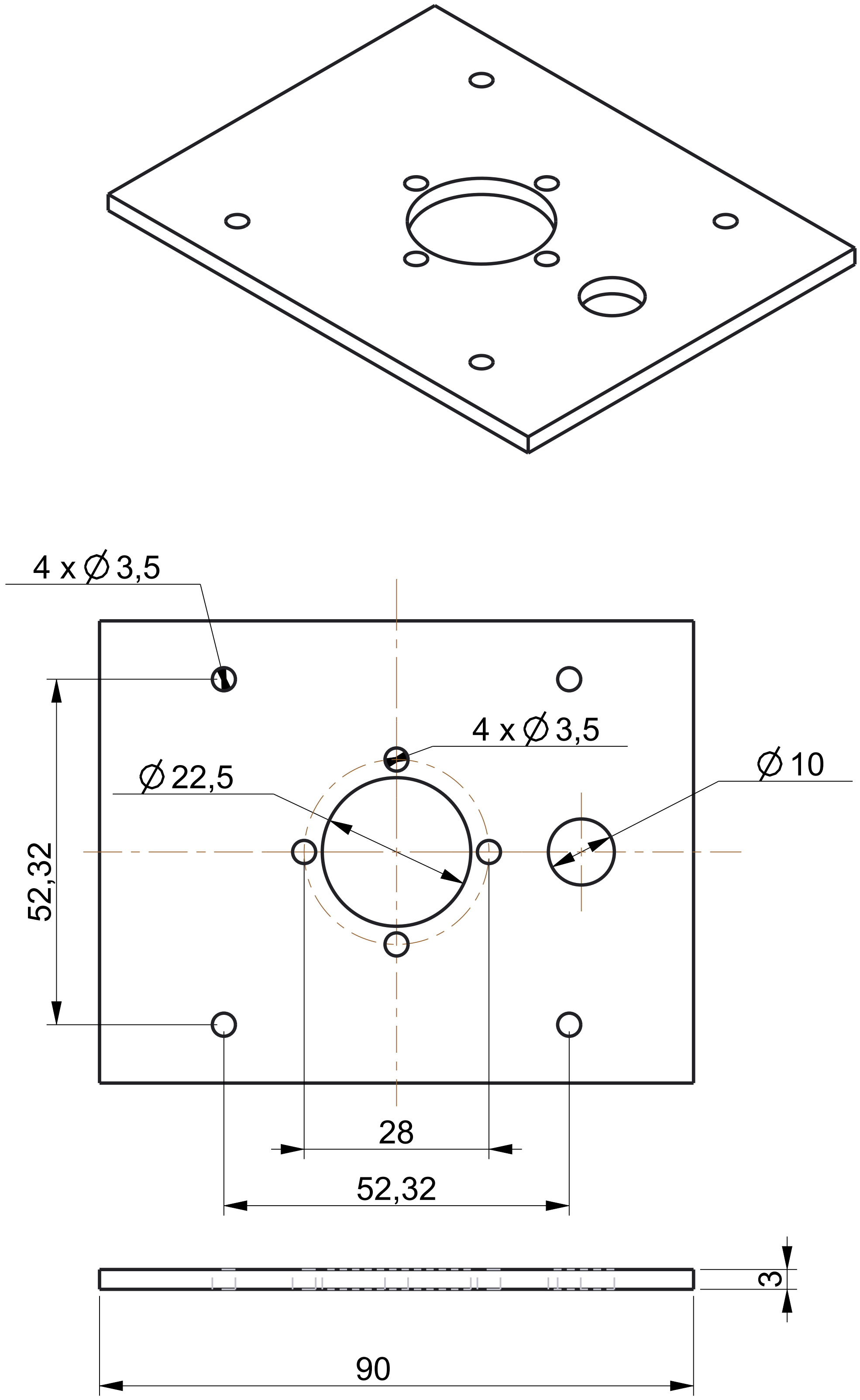
Schaal: 1:1

ARTURO BAHILLO RUIZ

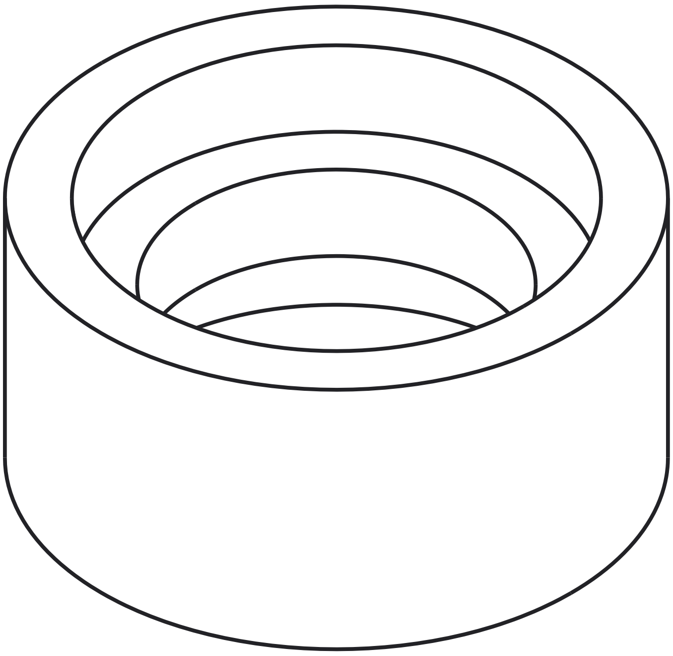
Blad: 7 12

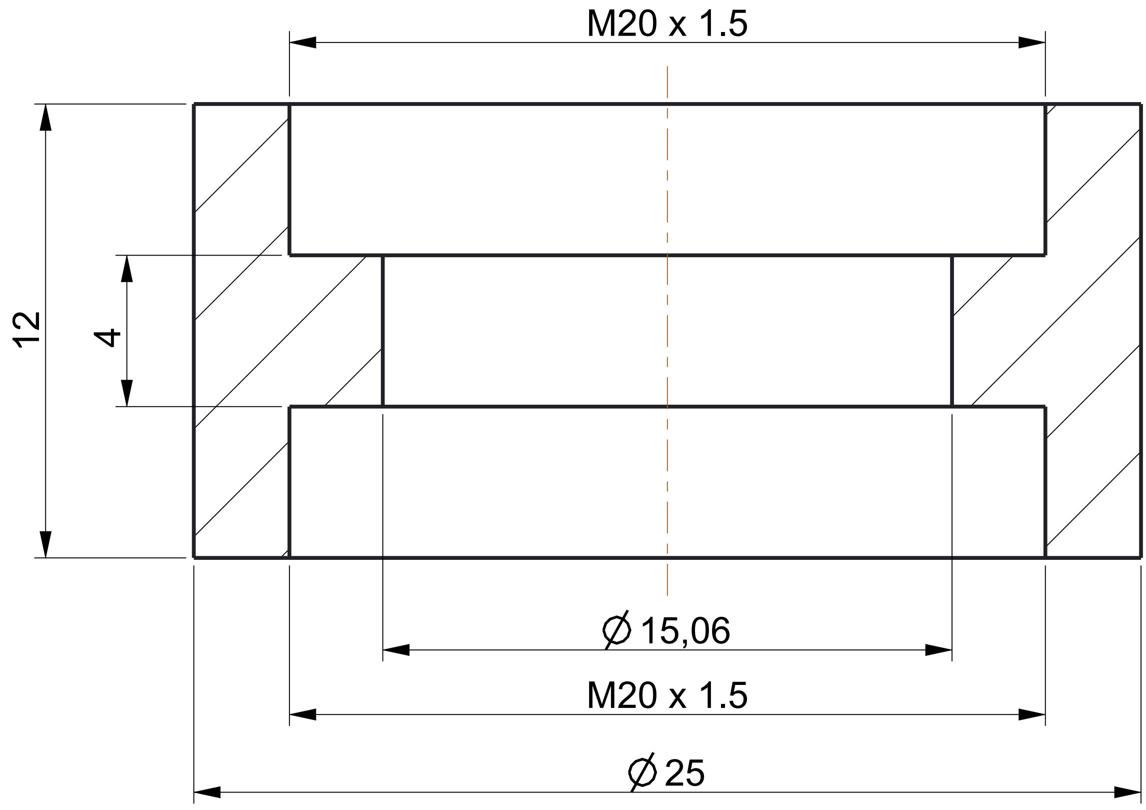
Model: CALENTADOR DWG: HEATER_PIECE

A4



ISO-symbool	katholieke hogeschool associatie KU Leuven vives	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	
Model			
Tekening	HOPPER PLATE	31/05/2016	
Gezien			
Schaal: 1:1	ARTURO BAHILLO RUIZ	Model: HOPPER_PLATE	DWG: HOPPER_PLATE
Blad: 8	12	A4	

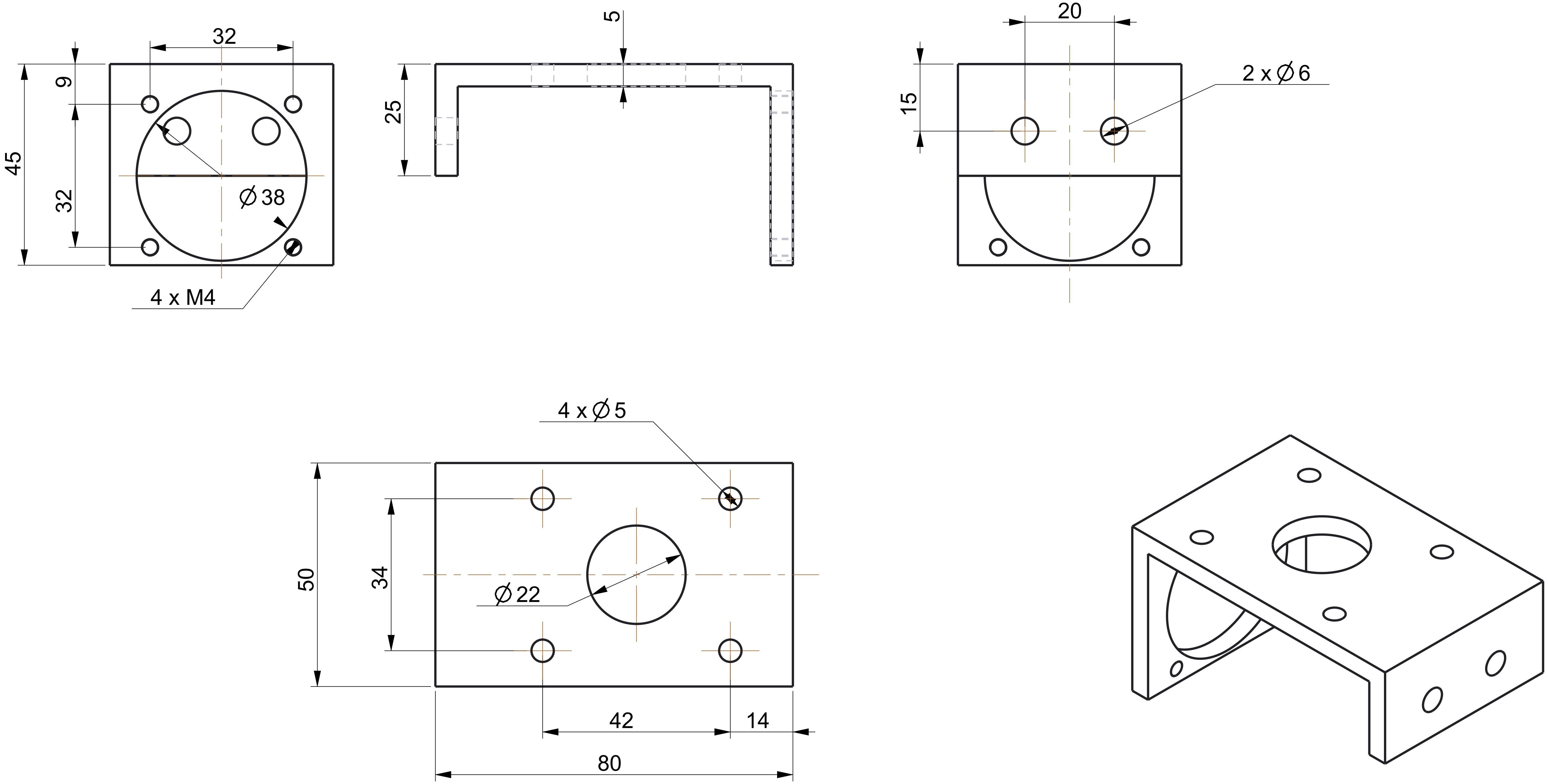




ISO-symbool	katholieke hogeschool vives associatie KU Leuven	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	
		Model	
		Tekening	JOINT	31/05/2016
		Gezien	

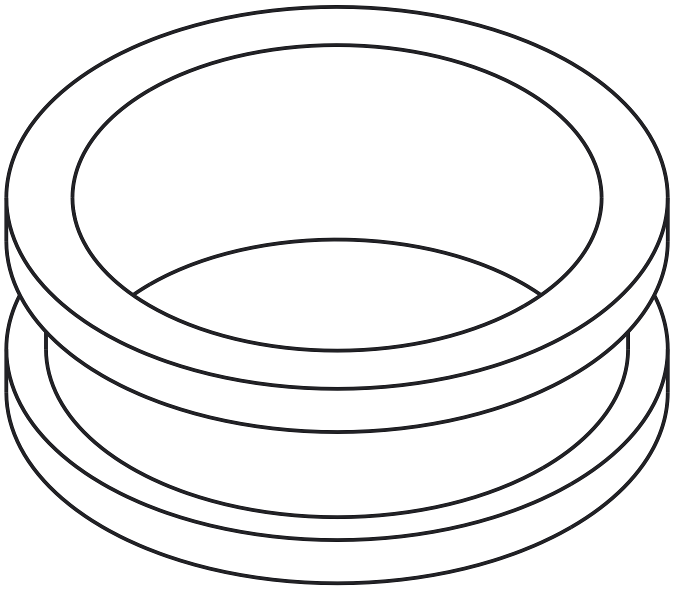
Schaal: 5:1	ARTURO BAHILLO RUIZ	Model: JOINT	Blad: 9 / 12 DWG: JOINT

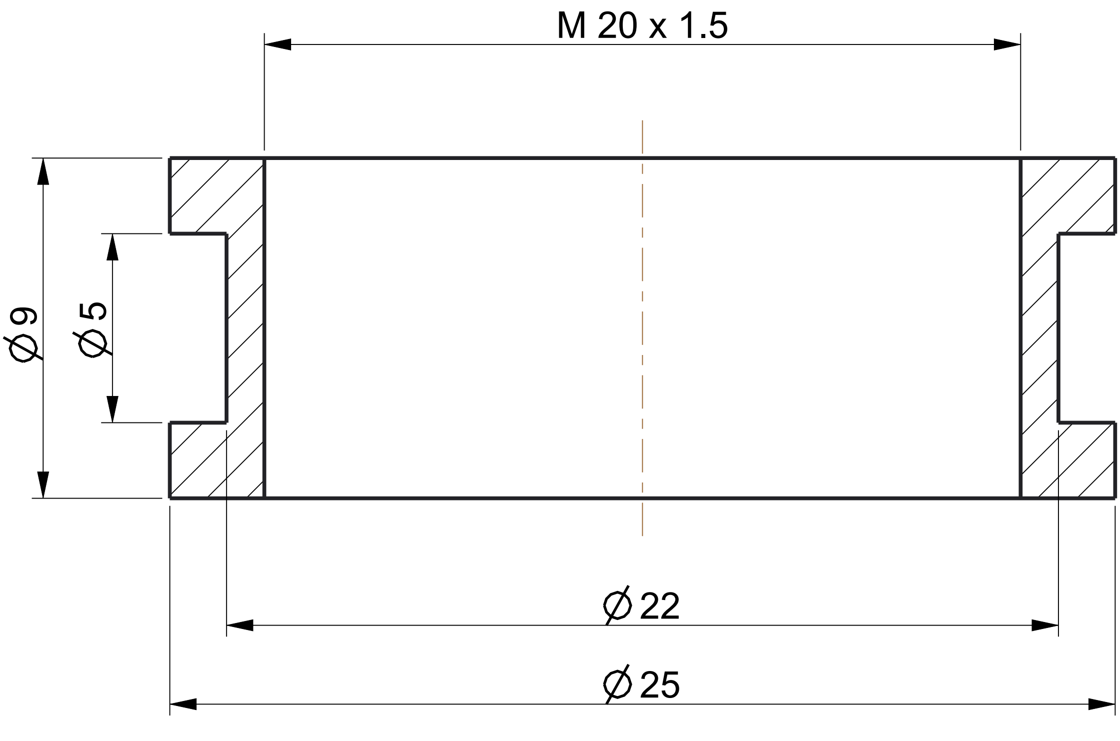
A4



ISO-symbool	katholieke hogeschool vives associatie KU Leuven	Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model	
			Tekening	SUPPORT PLATE 01/06/2016
			Gezien	
Schaal: 1:1	ARTURO BAHILLO RUIZ		Blad: 10 12	
			Model: SUPPORT	DWG: SUPPORT

A3





ISO-symbool

katholieke hogeschool vives
associatie KU Leuven

Doorniksesteenweg 145
8500 Kortrijk
T +32 (0)56 26 41 20
F +32 (0)56 21 98 67

Model		
Tekening	SUPPORT JOINT	31/05/2016
Gezien		

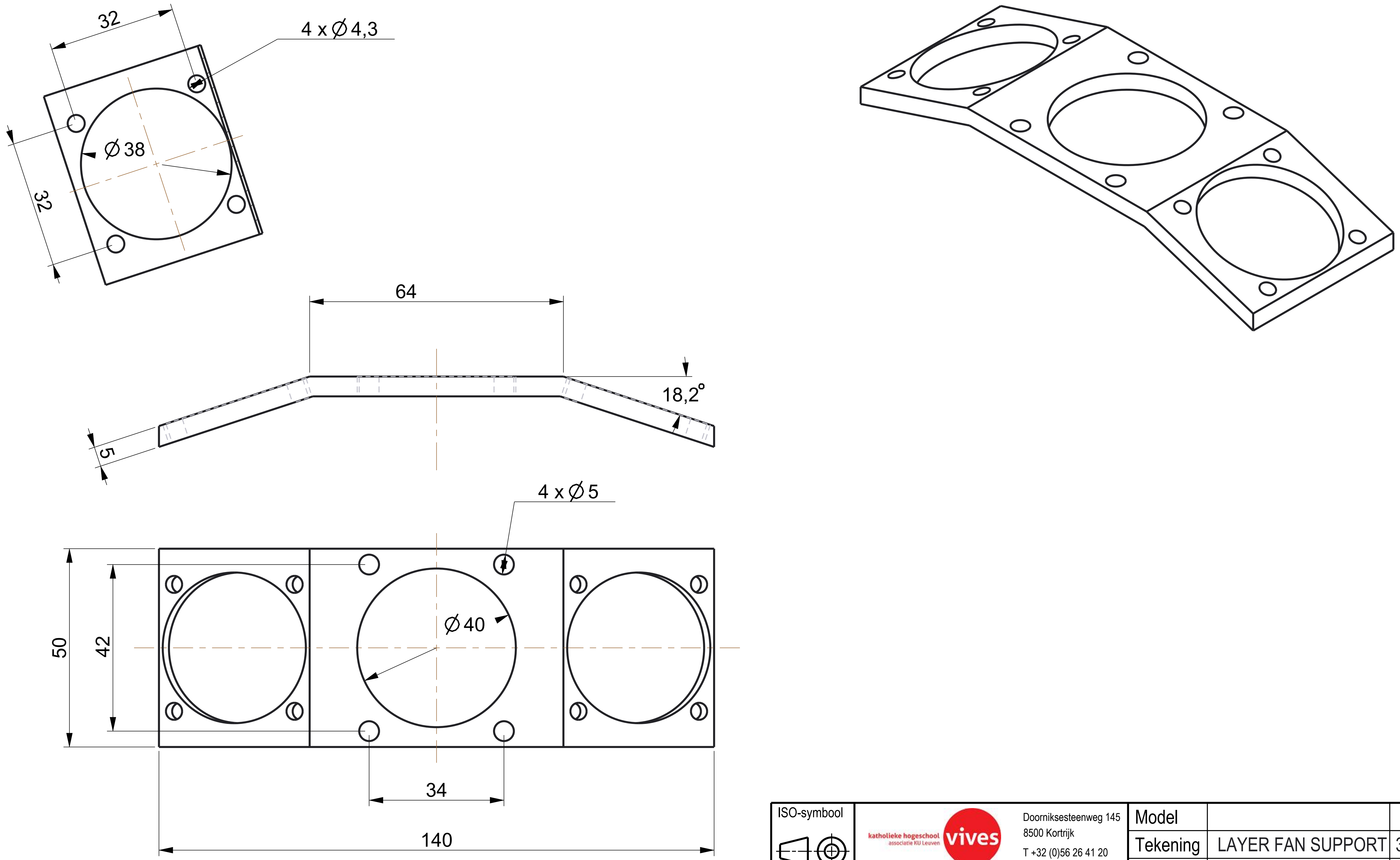
Schaal: 5:1

ARTURO BAHILLO RUIZ

Blad: 11 12

Model: FIXING_JOINT DWG: FIXING_JOINT

A4



ISO-symbool	katholieke hogeschool vives associatie KU Leuven Doorniksesteenweg 145 8500 Kortrijk T +32 (0)56 26 41 20 F +32 (0)56 21 98 67	Model		
		Tekening	LAYER FAN SUPPORT	31/05/2016
		Gezien		

Schaal:		Blad:
1:1	ARTURO BAHILLO RUIZ	12 / 12
	Model: LAYER_FAN_SUPPORT	DWG: LAYER_FAN_SUPPORT

A3