CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

MASTER THESIS 2021

OPTIMIZATION AND DESIGN OF A WRENCH USING SIMULATION TOOLS AND ADDITIVE MANUFACTURING

(DESIGN FOR ADDITIVE MANUFACTURING)

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Název diplomové práce anglicky:

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Design rules for various additive technologies
Topology and lattice optimization of selected part
Preparation of print data, Simulation of 3D printing process
Production, Post processing, Quality inspection

Seznam doporučené literatury:

Jméno a pracoviště vedoucí(ho) diplomové práce:

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Declaration

I declare that I have prepared this work independently, exclusively using the sources and literature listed in the list of cites sources. I agree to the use of the content of the work at the discretion of my supervisor.

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ABSTRACT

The aim of this project is to evaluate the effectiveness of the optimization techniques used in the design of a product and the feasibility of its manufacture with 3D printing. For this purpose, a reverse engineering process of a real and existing product on the market, a 14-17mm fixed double-mouth wrench, is carried out and its initial properties are analyzed. Then, with the help of Altair Inspire software, two optimization methods are applied: Topology Optimization and Lattice Structure. With the results obtained with both methods, a new design of the product is made and simulated to analyze its properties. Finally, they are produced with 3D printing and subjected to a series of tests to make a final comparison between the new properties and those of the original product.

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1. STRUCTURAL OPTIMIZATION

Structural Optimization (SO) is not a theory of its own, but it makes extensive use of theoretical results from several research disciplines [1]. As its name suggest, SO consist on follow some techniques to optimize the final product structure. In addition, SO has the potential to reduce not only the construction/manufacturing cost, but also the engineering cost by automating some repetitive task of the design process. For this reason it has become an important tool in the design process in different engineering and architectural applications.

Structural Optimization is not a modern concept, in fact it is possible to find indications of the use of this method thousand years ago. One of the best examples to explain how SO works is the evolution of the wheel design.

At the beginning a wheel was a simple stone cylinder whose only purpose was to roll. However, over the time, the necessities looked on it were been more complicated as the technologies developed. That is why the evolution of it design can be perfectly showed in *Picture 1*, where the changes of wheel design were always looking for lightweight, achieve a linear rolling and looking for the best material according with the operation conditions and the manufacturing costs.

Picture 1. Historical evolution of the wheel design.

When talking about SO, three structural optimization strategies can be distinguished: Size Optimization, where the aim is to find the optimal dimensions of the structural components; Shape Optimization, where the shape of the structure is parameterized and these parameters are optimized; and Topology Optimization, where the optimal spatial distribution of structural material or structural components is determined [2].

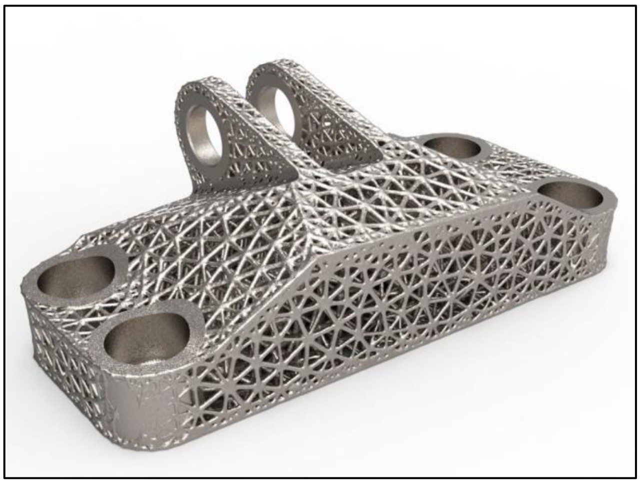
All these strategies can be implemented in the design process and can be combined to obtain a complete optimization. Generally Size Optimization use to be defined firstly and then the shape depends on the topology optimization, so these are used to be applied at the same time.

The most common disciplines used for applying these structural optimization strategies are: Lattice Structure Optimization, Topography Optimization and Topology Optimization.

1.1. Lattice Structure Optimization

Lattice Optimization (LO) is one of the most important techniques in Structural Optimization. LO consist on fill the design space with an optimized lattice structure that let the part operate correctly without losing important properties. This technique lightens the parts and structures manufactured with this method.

Make a lattice structure always has been a very complicate task and that is why it has a lot of limitations. However thanks to Additive Manufacturing (AM), it has become easier to manufacture this type of structure. Despite this, manufacturing constraints still exist for AM fabricated lattice structures, which have a significant influence on the printing quality and mechanical properties of lattice struts. For this reason is very important that designers has the knowledge of the manufacture properties and the limitations of it.



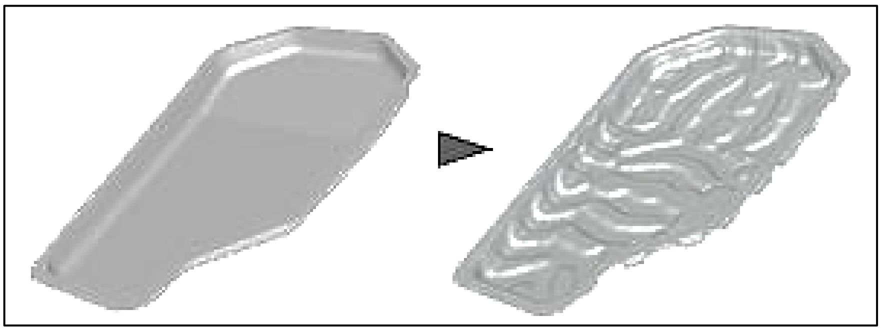
Picture 2. Example of Lattice Optimization

This technique is used in many different applications where is important to maintain the shape of the part but with a low weight. One of the applications where this technique has had more impact has been the biomedical world. LO is very useful in medical devices and implants where is necessary an osseointegration, because lattice structures increase the surface area which is perfect for better osseointegration and also helps the body to accept correctly the implant [3].

1.2. Topography Optimization

Topography Optimization is a mathematical method which consist on optimize the material layout within a given design space, for a given set of loads, boundary conditions and constraints with the goal of maximizing the performance of the system. However this kind of optimization is only available for thin and watertight geometries, due to this technique achieve lightness the part without obtain gaps in the surfaces of it.

The main idea of Topography Optimization is to generate beads or swages along the surface in order to maximize stiffness and resonant frequency at the same time that achieve the lightweight part.



Picture 3. Example of Topography Optimization

This technique is perfect for big parts which have big thin surfaces and are difficult to lightweight. One example of a part optimized with this technique is an oil pan of a car motor.

1.3. Topology Optimization

Topology Optimization (TO) is a mathematical method, similar to Topography Optimization, that also optimizes material layout within a given design space, for a given set of loads, boundary conditions and constraints with the goal of maximizing the performance of the system. However the main difference is that, in this case, obtain gaps in the surface is not a problem if the part is still correctly working.

The basic concept consists on using only the material strictly required to achieve the correct operation of the part manufactured. To do that, the conventional TO formulation uses a finite element method (FEM) to evaluate the design performance. In this way it is possible to eliminate excess material reducing the weight and maintaining the properties of the part.

Topology Optimization has a wide range of applications in aerospace, mechanical, biochemical, and civil engineering. Currently, engineers mostly use it at the concept level of a design process. However, due to the free forms that naturally occur, the result is often difficult to manufacture. For this reason a strong link has been established between Topology Optimization and Additive Manufacturing (AM).

Picture 4. Example Topology Optimization

Structural optimization is one of the most intensively investigated research areas in engineering, but recently, topology optimization has become the most popular engineering subfield.

The origins of topology optimization are difficult to determine it precisely because there are some papers published in 1904 which has references to papers published in 1870. However, during the first years of the century, the data related with this field was very limited so there was almost no knowledge about the publications in topology optimization until 1970, when appears the digitalization.

As technology advanced, the idea of leveraging computing power to speed the development of structures that are optimized for characteristics such as mass and stiffness first emerged in the world of academia. That is why in the last years the topic has been highly developed.

The peak of the TO came with the emergence of the Additive Manufacturing (AM), because the AM made possible the manufacturing of geometrical complex parts thanks to its versatility. Since both aspects were combined, the topic has been highly developed. Nowadays the topology optimization is combined with additive manufacturing to design geometrical complex parts [4].

2. ADDITIVE MANUFACTURING

2.1. Introduction

2.1.1. Definition

Additive Manufacturing (AM) is the process which consist on modeling products in 3D by taking the information from a computer-aided design (CAD) file that is later converted to a stereolithography (STL) file. In this process, the drawing, made in the CAD software, is approximated by triangles making a mesh and sliced containing the information of each layer that is going to be printed. It requires the use of a 3D printer that takes the information provided by the computer and prints the product layer by layer [5], [6].

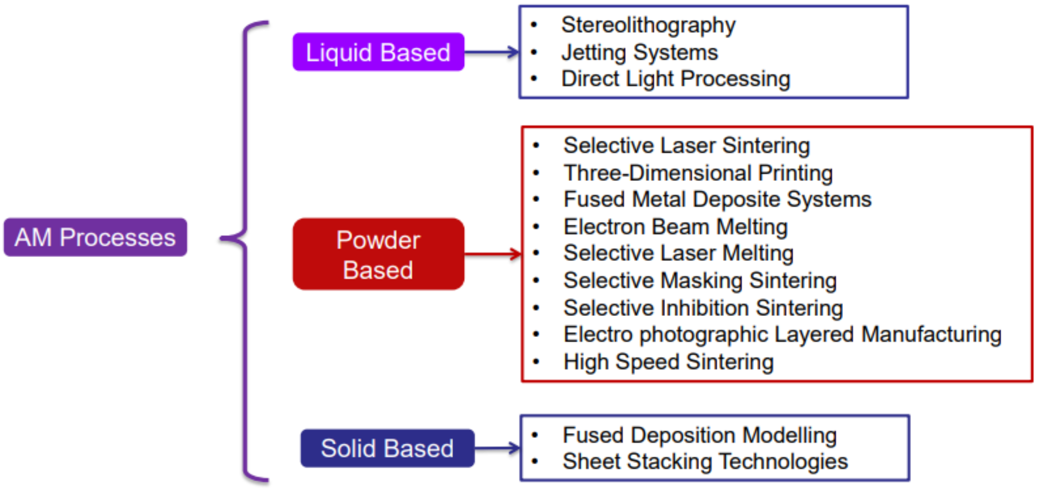
2.1.2. History

This process is quite novel, in fact, although there exists some paper related with this field in the middle of the 20th century, the first machines were invented at the beginning of 1980.

Thanks to the developing of CAD software, AM has gained a lot of popularity last years and nowadays is still developing with a promising future in plenty applications of design and manufacturing. Besides now exist the possibility of working with different materials and different levels of details, since a simple prototype with low quality to a specific part with high accuracy and some properties very strict.

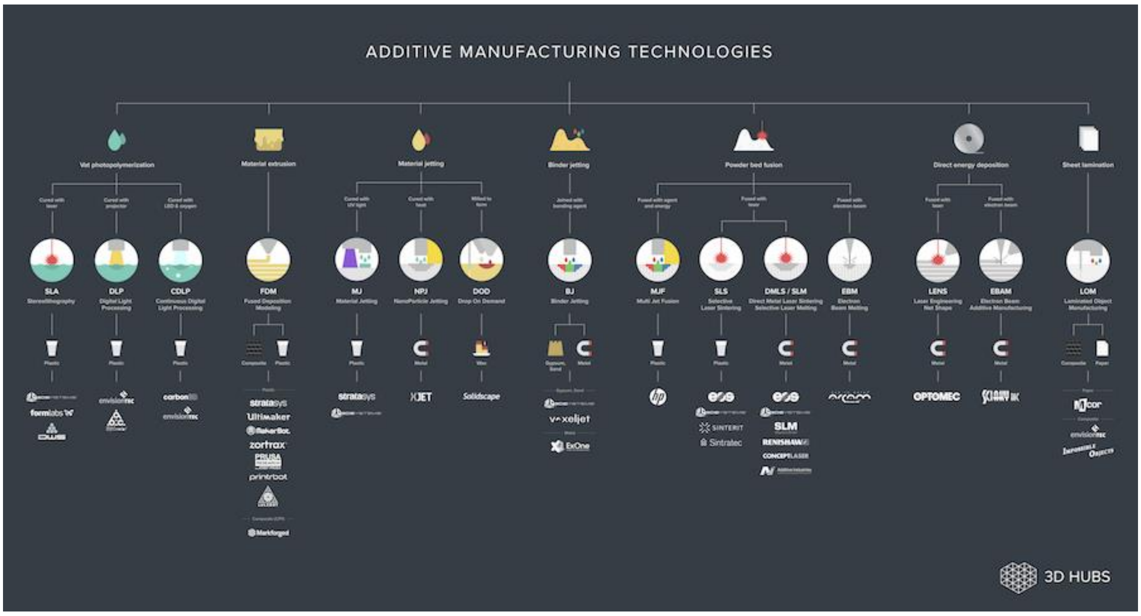
2.2. Classification

Nowadays exist many different AM process according to the power source, the material used and the material state.



Picture 5. Major AM processes based on Hopkinson and Dicken's classification

For this reason it is possible to choose between plenty of different additive manufacturing technologies as it is show in *Picture 6*.

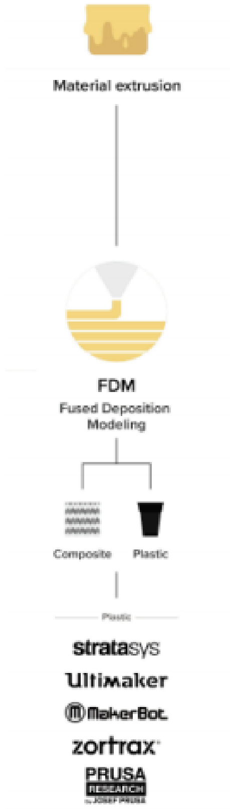


Picture 6. AM Technologies

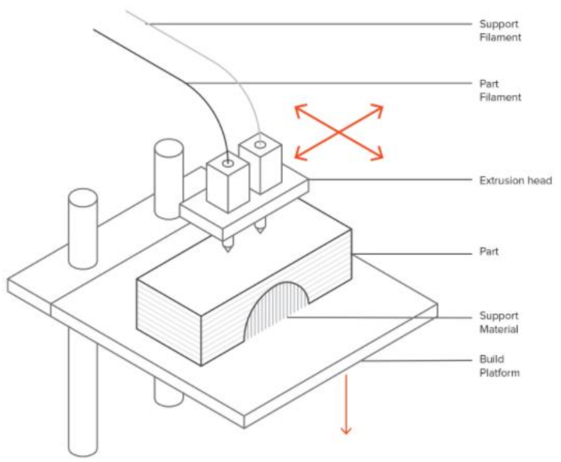
2.2.1. Material Extrusion

Material extrusion technologies extrude a material through a nozzle and onto a build plate. The nozzle follows a predetermined path building layer by layer.

- **Fused Deposition Modeling (FDM)**



Fused Deposition Modeling (FDM) is an additive manufacturing process that belongs to the material extrusion family. This process consists on depositing melted material in a pre-determined path layer by layer. The materials commonly used are thermoplastic polymers and come in a filament form.



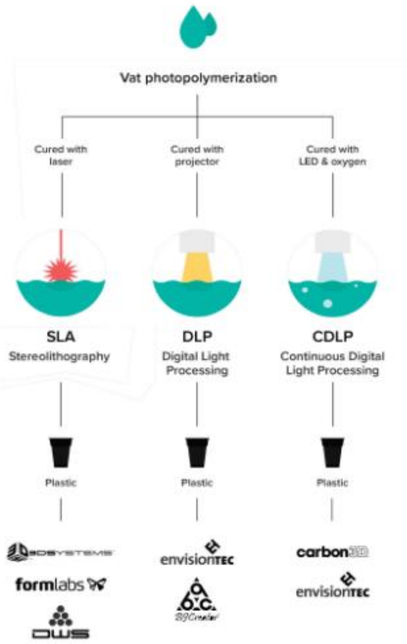
Picture 7. FDM technology

FDM is the most cost-effective way of producing custom thermoplastic parts and prototypes using a wide range of thermoplastic materials. However FDM has the lowest dimensional accuracy and resolution compared to other 3D printing technologies, so it is not suitable for parts with intricate detail. In fact, a postprocessing is required for a smooth finish, because the parts manufactured with this technology used to have visible layer lines. A designer should keep in mind the capabilities and limitations of the technology when fabricating a part with FDM, as this will help him to achieve the best result.

All in all, FDM is the most widely used 3D Printing technology, in fact, it represents the largest installed base of 3D printers globally and is often the first technology people are exposed to.

2.2.2. Vat Photopolymerization

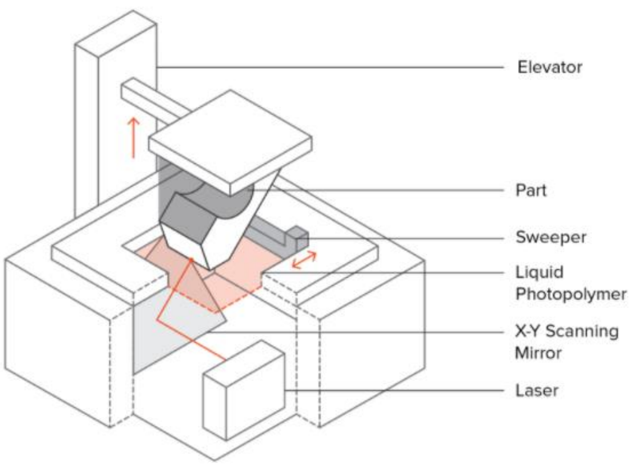
Photopolymerization occurs when a photopolymer resin is exposed to the light of a specific wavelength and undergoes a chemical reaction to become solid. There are several additive technologies utilize this phenomenon to build up a solid part one layer at a time: SLA, DLP, MSLA and CDLP.



- **<u>Stereolithography (SLA)</u>**

Stereolithography (SLA) is the basic additive manufacturing process that belongs to the vat photopolymerization family. In SLA, an object is created by selectively curing a polymer resin layer by layer using an ultraviolet (UV) laser beam. The materials used in SLA are photosensitive thermoset polymers that come in a liquid form.

SLA is famous for being the first 3D Printing technology because its inventor patented the technology back in 1986. Besides this technology is the most cost-effective 3D printing technology available to produce parts with high accuracy and with intricate details. However, SLA parts are generally brittle, not suitable for functional prototypes and support structures and post processing are always required [7].

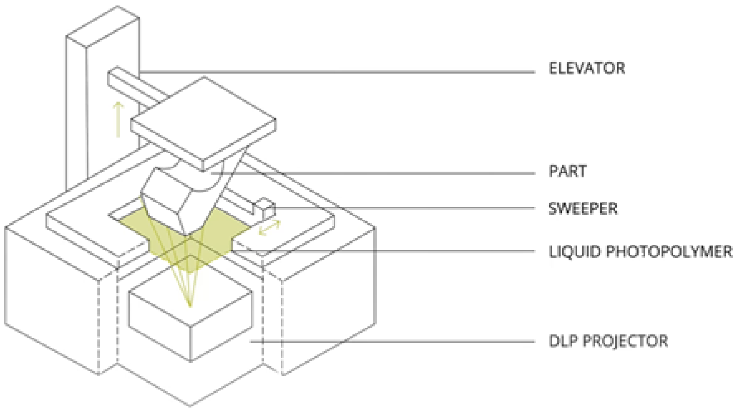


Picture 8. SLA technology

- **Digital Light Processing (DLP)**

Digital Light Processing (DLP) follows a near identical method of producing parts when compared to SLA. The main difference is that DLP uses a digital light projector screen to flash a single image of each layer all at once.

As the projector is a digital screen, the image of each layer is composed of square pixels, resulting in a layer formed from small rectangular bricks called voxels. DLP can achieve faster print times compared to SLA for some parts, as each entire layer is exposed all at once, rather than tracing the cross-sectional area with a laser.



Picture 9. DLP technology

- **Continuous Digital Light Processing (CDLP)**

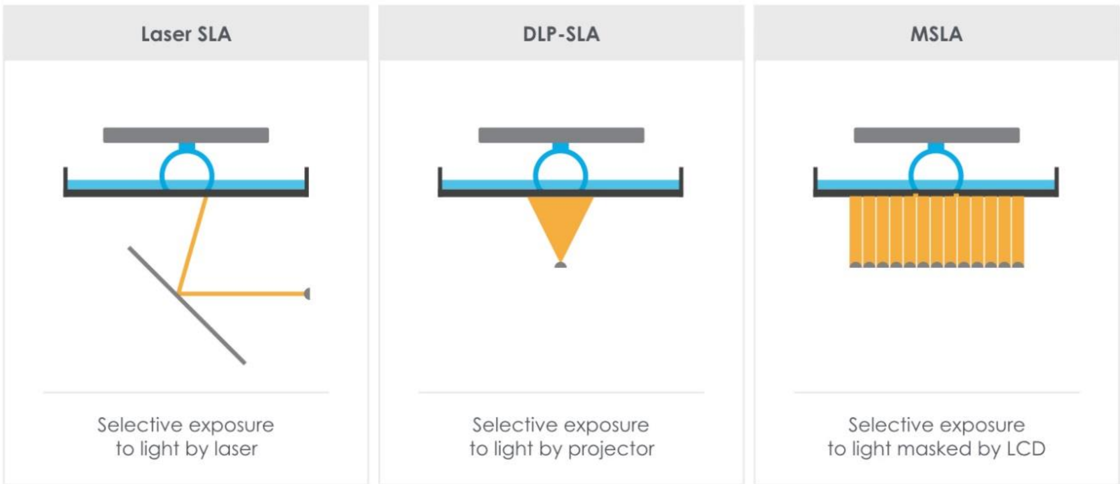
Continuous Direct Light Processing (CDLP) (also known as Continuous Liquid Interface Production or CLIP) produces parts in exactly the same way as DLP. However, it relies on the continuous motion of the build plate in the Z direction (upwards). This allows for faster build times as the printer is not required to stop and separate the part from the build plate after each layer is produced.

- **Masked Stereolithography (MSLA)**

Masked Stereolithography (MSLA) is based in the same concept to obtain the parts, however this technology goes one step further replacing the projector of the DLP with an LCD display and a bright LED light.

In this way the machine has a vat of resin sits above the LCD, separated by a very thin layer of Fluorinated Ethylene Propylene (FEP) plastic. The LCD displays the desired shape by turning off individual pixels where the resin needs to be cured, while all the other pixels are illuminated. Also it has a bright LED beneath this LCD, and light can only travel past the LCD via the pixels that are not illuminated. This light passes through the LCD and FEP sheet, allowing the resin squished between the build platform and the FEP sheet to be partially cured. The build platform then lifts to break the surface tension between the cured resin and the FEP sheet and repositions itself for the next layer to be cured.

Like the other methods, this process is repeated layer by layer until the complete model has been printed. However this process is many times quicker than the LASER SLA technology, owing to the fact it creates an entire layer with one pass. Also the LCD Display is cheaper than the projector used in DLP [8].



Picture 10. Comparation of Vat Photopolymerization Process

3. DESIGN RULES

Due to the differences in AM technologies, processes and materials used, functional and geometrical properties of manufactured parts can vary dramatically. Planning decisions to select the appropriate AM process and material based on specific application requirements can be rather involved. Designers today are challenged with a lack of understanding of AM capabilities, process related constraints and their effects on the final product. For this reason is important to talk about the Design Rules according to the AM process and material selected.

To design a new product is not an easy task. Designers must think not only in the shape and size of the part, but also in the material and the manufacturing process of it. In addition all these considerations are directly related, which makes the design process harder. Design Rules are a series of steps which are highly recommend to follow by designers in order to achieve the best product possible taking into account all the design considerations and constrains [9].

In this project the part is going to be manufactured with an AM process, so let see whose are the design rules for this king of manufacturing process:

3.1. Size

The size and the dimensions of the final product are vital for it design and manufacturing. Normally the size depends on the operations that is going to realize the final part, so is one factor difficult to change.

According to the product size a specific 3D printer should be use. Generally the AM machines are classified by capacity of production. As bigger the product is, as bigger must be the 3D printer to manufacture it and this use to increase costs.

Same problem appears when the part is very small or requires a lot of accuracy. 3D printers have work limitations and sometimes is impossible to print some parts because of its size. For example holes with diameter < 0.5 mm are not possible to print because the print filament is not allowed to do that.

3.2. Shape

As the size, the shape normally depends directly on the operations that is going to realize the final part and is difficult to change it. However it can be optimized with different methods that have been mentioned early in this paper. The techniques more used are: Topology Optimization, Topography Optimization and Lattice Structures. Each one optimizes with specific ways and the results are completely different.

Nevertheless if the shape is very complicate, it will cause some troubles during the printing because in this kind of technology there exist some limitations as it has been mentioned in the size point.

3.3. Material

Select the material of the final product is another vital task. This decision use to determine the kind of AM process and 3D printer which should be selected to manufacture the part. Also select the material is important to design because the properties of it will determine the amount of material required to comply with the initial specifications of the part.

In AM is common to use plastics because are cheaper than other materials and are easy to be used in the 3D printers. However nowadays there exist 3D machines capable of working with a large variety of materials. Especially last years it has been developed more than the rest the use of metal in this kind of technology.

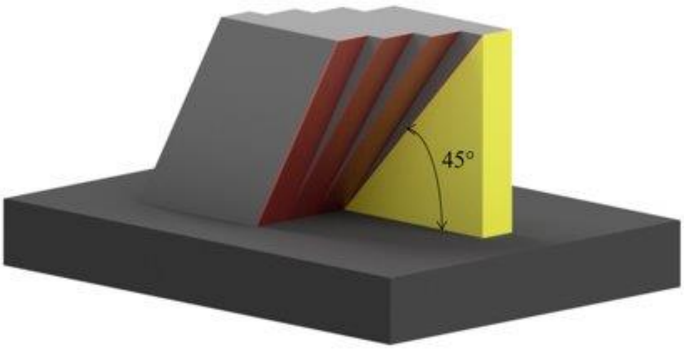
Depends on the material chosen to manufacture the product, different requirement is necessary to consider in order to obtain a quality product with AM.

3.4. Orientation and supports

The colocation of the part on the printing plate is crucial, because that will determine the quality of the impression, the number of supports needed and other properties of the part like heat distribution and stiffness [10], [11].

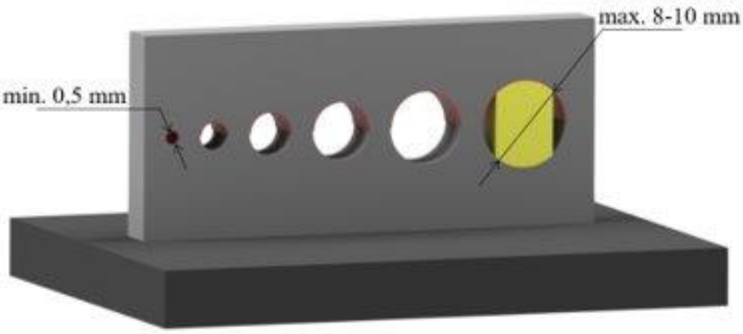
It is worth mentioning that reduce the number of supports is important to achieve a faster printed and to waste less material, so the objective is use only the strictly necessaries supports. But when is necessary to use supports?

- When the angle between the element and the print table is lower than 45º. This angle value can vary depending of the material used, but generally it is used 45º as the limit to add or no support.



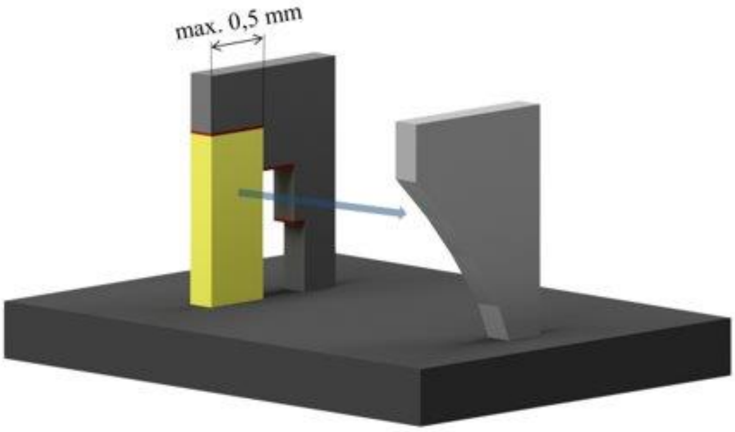
Picture 11. Angle limit for add support

- When the hole diameter is > 8-10 mm is highly recommended to add supports to avoid deformations.



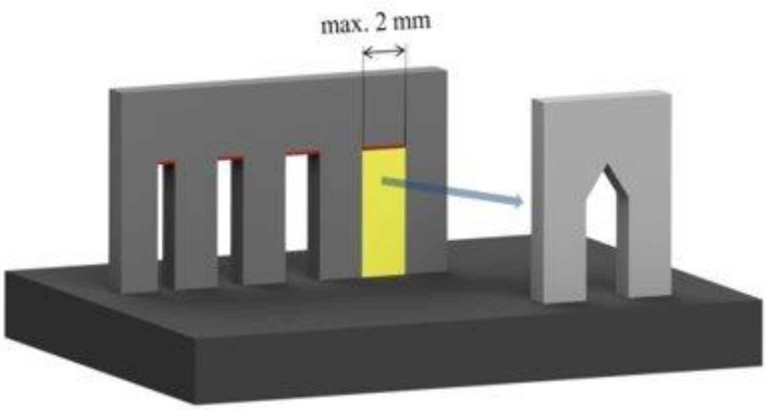
Picture 12. Diameter limit to add support

- In cases where there are sudden changes of component geometry, forming an angle to horizontal plane > 45° and it appears a cantilever longer than 0.5 mm. However if the transition of the shape is continue with concave or convex shape, the part stands on its own.



Picture 13. Support required in sudden changes of component geometry

- When the distance between two points without supports is > 2 mm.



Picture 14. Maximum distance between two points without supports

Finally, apart of all this cases, is highly recommended to add support on the part face which is in contact with the print table, because if it is printed directly, there use to appear errors and imperfections when the part is remove from there [12], [13].

3.5. Simulation

Simulate the manufacturing process of the part + structure supports with a design software is recommended to avoid waste of material due to defects and errors during the manufacture process. With this kind of software like Altair Inspire, it is possible to simulate not only the forces which suffer the part, but also different kind of design optimizations and the hole printing process.

3.6. Postprocesing

In this kind of manufacturing, postprocessing cost can vary between 60% and 300% respecting impression cost. For this reason is very important try to reduce the postprocessing tasks like for example reducing the number of structure supports or using the techniques required depending of the kind of technology used and the rest of parameters mentioned in the design rules.

Picture 15. Removing the supports

As the majority of the postprocessing task are related with supports, like remove it or smooth the surfaces which have it, sometimes is used a different material to manufacture these supports in order to facilitate the process.

4. PART DESIGN

4.1. Original

4.1.1. Selection

In order to analyze and study the hole process of design with the application of different optimizations, a part has been selected as an example of design and manufacturing process.

To select the correct part has been considered different characteristics as size, operations of the parts, viability of applying the optimization methods and the capacity to can be manufactured with AM. With all this in mind, a fixed wrench has been selected to do its design about, because is a small tool which can be manufactured with AM and which has different properties whose are perfect for this study.

4.1.2. Initial Data

Once the product has been selected the next step is determine the size and the strict dimensions of the part. Between all the classes of fixed wrenches which exist in the market, the selected one is a 14-17 mm from the TONA brand. The main reason of that selection is because in the laboratory of Mechanical Engineering of the CTU there is the real one, so making a redesign of that tool could give us the possibility of compare the original part with the manufactured using AM.

Picture 16. Real fixed wrench 14-17 mm

The information of the specific wrench is looked in the original catalog of the TONA brand. This tool belongs to the group of *DOUBLE OPEN FACE METRIC WRENCH DIN 895* and has the following properties:

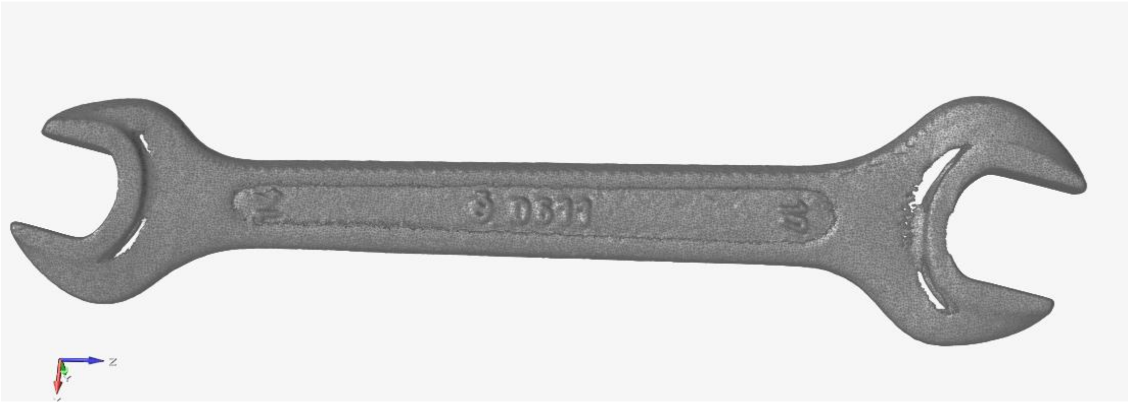
- DIN 895 - ISO 1085 - ISO 1711-1 – ISO691 – ISO 3318
- Wrench jaws inclined 15º from the axis of the wrench body (working angle 30º).
- High quality carbon steel
- Phosphating treatment

Obj.číslo	A1 (mm)	A2 (mm)	L (mm)	C (mm)	B1 (mm)	B2 (mm)	g	Cena (bezDPH)	Cena (sDPH)	EAN
E114018	14	17	162	6,0	28,5	34,5	72	47,11	57,00	3258951140185

Picture 17. Data from TONA catalog (https://tona.cz/katalog/)

4.1.3. Reverse engineering

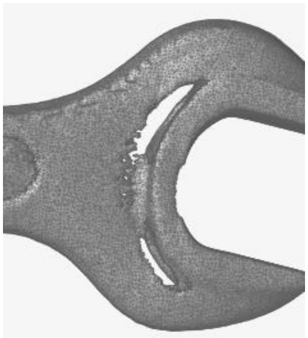
Once the specific part has been selected, next step is to obtain a 3D model of the original one. There are plenty of options to do that but make use of new technologies could facility the design task. That is why a scanning of the original fixed wrench is used to obtain a 3D model. Using the scanning machine of the Mechanical Laboratory of the CTU the following result was obtained:



Picture 18. Fixed wrench scanned

Not always new technologies work as perfect as it could be expected and sometimes is necessary to keep working to obtain the results that are looking for. In this case the 3D model obtained via scanning has some errors between the connection of the body and the mouths of the fixed wrench.

As it can be seen, the mesh obtained has some imperfections which are caused by the lights and the shadows of the fixed wrench during the scanning. This kind of problems are common to appear and could be repaired to obtain a close STL file editable, however this process requires too much time and the results not always are as accurate as expected.



Picture 19. Scanning

For this reason a combination between the mesh obtained by the scanner and the dimensions of the original fixed wrench are used to obtain the 3D model. Solidworks software is used to model a solid using the scanning mesh as a template and correcting the imperfections according to the original dimensions.

Picture 20. Solidworks model

Once the 3D model was finished in SolidWorks, it was exported to Altair Inspire to start with the optimization process.

Picture 21. Altair Inspire model

4.1.4. **Analysis**

With the inverse engineering process complete and the 3D model of the original fixed wrench obtained, it is possible to know more properties about it by doing a complete analysis with the software Altair Inspire.

4.1.4.1. **Material**

Before start with the analysis is crucial determinate the material of the product. The real fixed wrench is made by high quality carbon steel, so it would be perfect to simulate and manufacture new designs with the same material. However it has not been possible to use a metal 3D printer to manufacture the parts, but it will not be a problem because, as the original part is going to be manufactured too with the same material, the comparative between the original and new designs optimized will be valid. For this reason the study will focus on plastic PLA, which is the material which is going to be used to manufacture all the parts.

Polylactic acid or polylactide (PLA) is a thermoplastic polyester which is very popular for being very economical and easy to use in additive manufacturing, which is perfect to obtain prototypes. This material has the following properties:

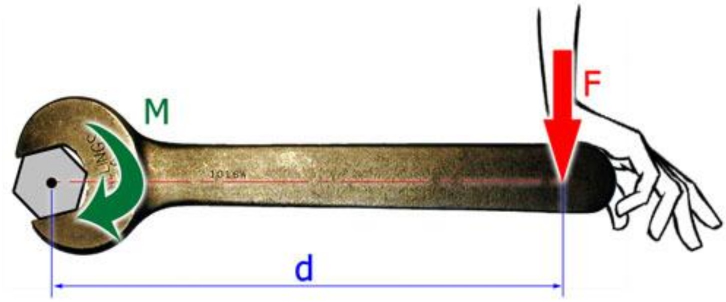
Material	E	Nu	Density	Yield Stress	α	λ
PLA	3.450E+3 MPa	0.390	1.240E-6 kg/mm3	63.500E+00 MPa	41.000E-06 /K	130.000E-06 W/(mm*K)

Table 1. PLA properties

4.1.4.2. **Forces**

For this study is very important to know how the original tool behaves during normal operation. For this purpose, the behavior of the fixed wrench is analyzed in relation to the forces to which it is subjected.

A fixed wrench is used to tighten and loosen nuts, movements that require moment of force. The case of maximum moment is given when the distance “d” is maximum, for this reason is interesting to analyze in that point.



Picture 22. Forces during the operation

As this tool has two mouths, is necessary to simulate two different load cases which simulates a real operation of the original fixed wrench:

1. <u>Load case 1:</u> The mouth of 17 mm is fixed and the force is applied over the other mouth. This simulates the operation of the tool using the mouth of 17 mm.

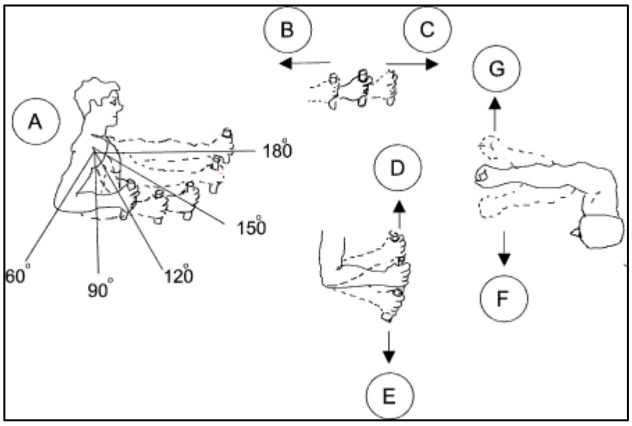
Picture 23. Load case 1

2. Load case 2: The mouth of 14 mm is fixed and the force is applied over the other mouth. This simulates the operation of the tool using the mouth of 14 mm.

Picture 24. Load case 2

Force value depends on the strength capacity of the user, so to estimate that value it is necessary to determinate some suppositions.

Firstly the force value is going to depend only on the arm strength of the user, because the object studied is a hand tool. Doing a research study in internet, it has been founded that there are many different movements analyzed to study the arm strength. However for this tool the movements that looks like more to the real operation are the movements F and G from the *Picture 25*. Calculating the average of the forces for different elbow angles from the *Table 2*, the value obtained is 53.3 N, but rounding the study should be done with a force value of 50 N.



Picture 25. Arm strength movements

A	B		C		D		E		F		G	
	L(N)	R(N)	L(N)	R(N)	L(N)	R(N)	L(N)	R(N)	L(N)	R(N)	L(N)	R(N)
180^{O}	177.6	184.8	149.6	177,6	32	49,6	46,6	60,8	46,6	71,2	28,8	49,6
150^{O}	149,6	199,2	106,4	149,6	53,6	64	64	71,2	53,6	71,2	28,8	53,6
120^{O}	120,8	149,6	92,8	128	60,8	85,6	74,4	92,8	71,2	78,4	36	53,6
90^{O}	113,6	132	78,4	128	60,8	71,2	74,4	92,8	56,8	64	36	56,8
60^{O}	92,8	85,6	78,4	120,8	53,6	71,2	60,8	71,2	42,4	60,8	L	R

Table 2. Arm strength values from USA (test on young men 80 % of 5th percentile group)

As it has been commented previously in this document, the material for the study is going to be different from the original object material, so the force value must be adapted to obtain logical results.

The original part is made by carbon steel and the new designs for this study are going to be made by PLA plastic. Comparing the properties of both material is logical that the carbon steel is considerably stronger than PLA plastic, so the force value must be reduced.

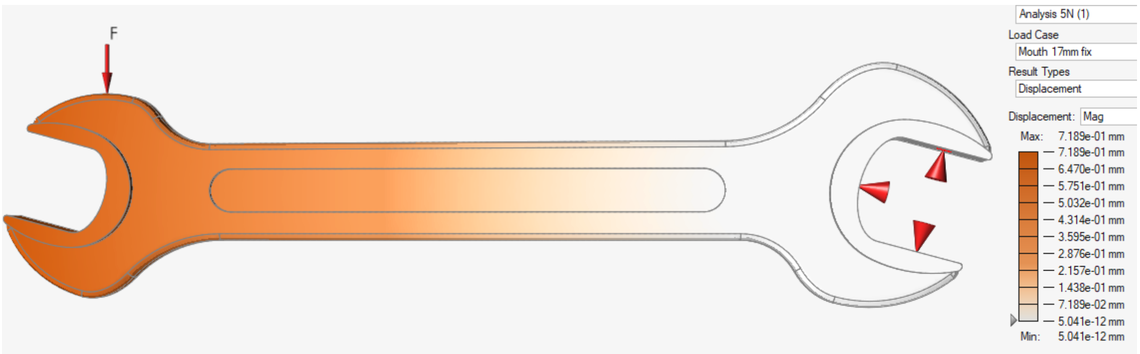
Finally it has been decided that the force value which is going to be used for the study of the new designs must be 5 N, 10 times lower than with the original material, but by doing this the results will be logical.

4.1.4.3. **Simulation**

Once the model of the original fixed wrench is made, the material is selected and the disposition of forces is distributed, the analysis in Altair Inspire can start. As it has been mentioned previously, two cases will be analyzed:

- ❖ <u>CASE 1</u>: The mouth of 17 mm is fixed and a force of 5 N is applied over the other mouth.
  - Displacement:

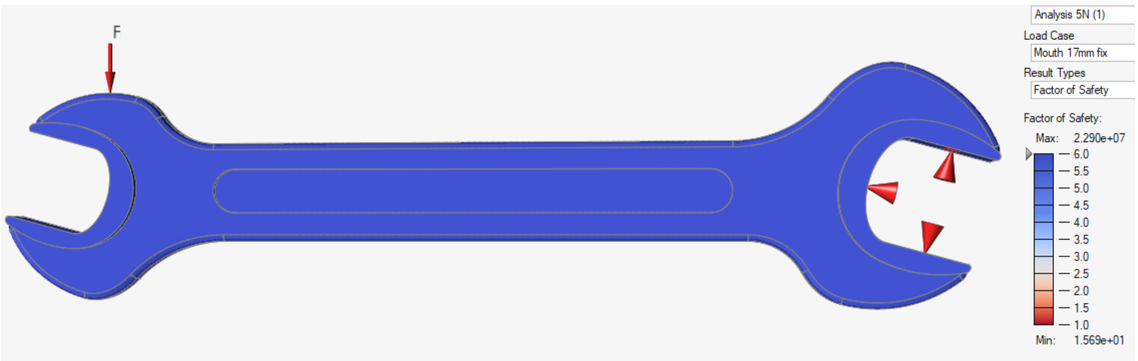
  As it can be seen in the *Picture 26*, the maximum displacement appears in the opposite mouth, where the force is applied. However the maximum value of this displacement is < 1mm, so the part is highly resistant.



Picture 26. Displacement

  - Factor of safety:

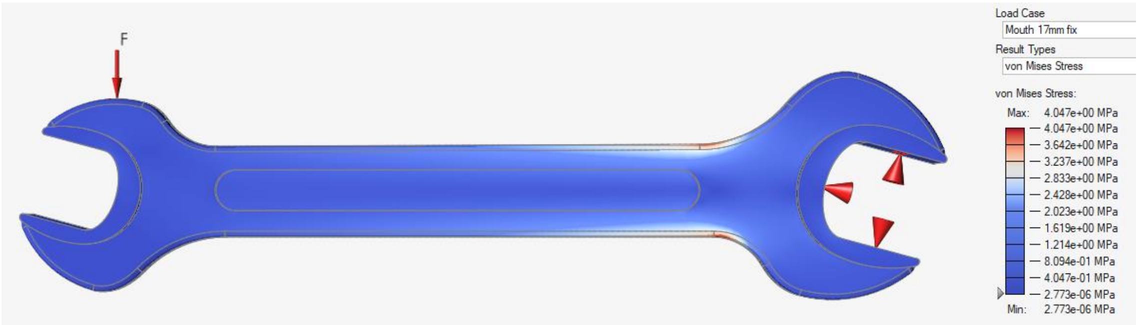
  In this case it can be seen that the hole part has the same blue color, which means that the factor of safety is ≥ 6 in all the points of the part.



Picture 27. Factor of safety

- Von Mises stress:

This result show how suffers the different areas of the part. In this case the critical area appears in the connection between the body and the mouth of 17mm. Is logical that that points are most critical because they are working in traction and in compression. However it suffers less than 4 MPa, which is bearable because PLA yield strength is 55 MPa, so it is far from broken.

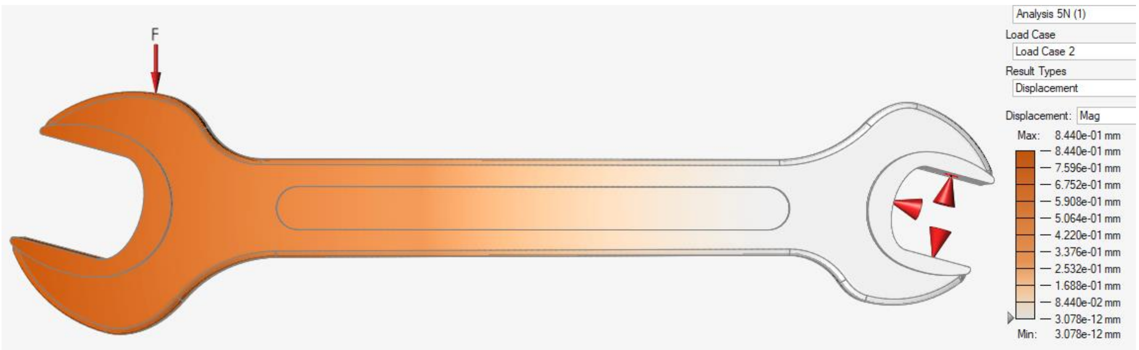


Picture 28. Von Mises stress

❖ <u>CASE 2</u>: The mouth of 14 mm is fixed and a force of 5 N is applied over the other mouth.

- Displacement:

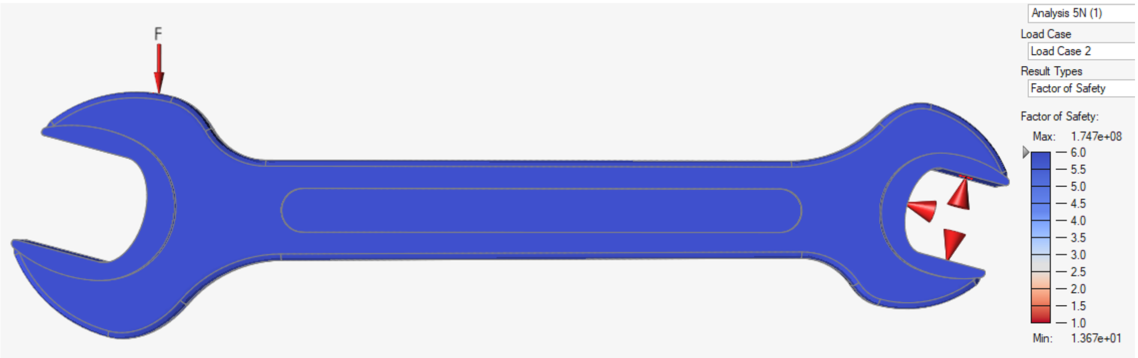
In this case the same occurs as in the mouth of 17mm, and although the maximum value of displacement is a little bit higher, it is still < 1mm which is insignificant.



Picture 29. Displacement

- Factor of safety:

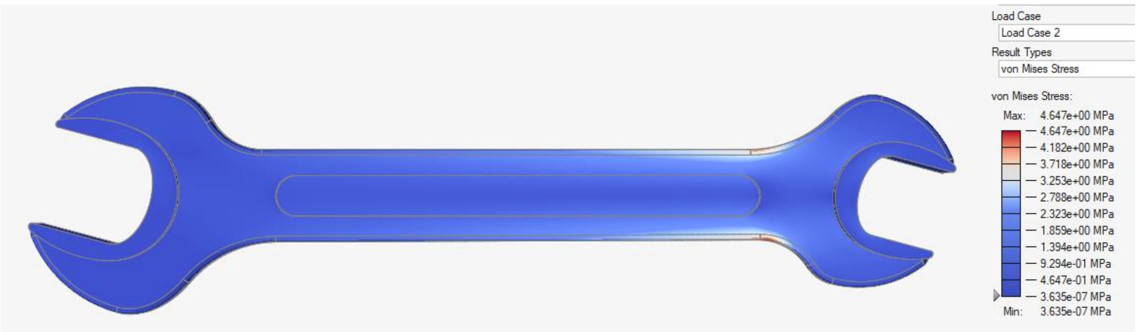
As in the CASE 1, the hole part has the same blue color, which means that the factor of safety is ≥ 6 in all the points of the part.



Picture 30. Factor of safety

- Von Mises stress:

As occurs in the other case, the critical area appears in the connection between the body of the tool and the mouth fixed because it suffers from traction and compression forces. However it suffers less than 5 MPa, which is bearable.



Picture 31. Von Mises stress

4.1.5. Manufacturing process

Working with the computer simulations is always an ideal situation because in the reality there are plenty of external aspects which can affect to the final properties and the operation of the part. For this reason is important to do some real experiments to analyze a real fixed wrench.

4.1.5.1. 3D printer

As it has been introduced before, a 3D printer is going to be used to manufacture all the parts design, but first is necessary some previous preparation.

Once the 3D model of the part is done, is necessary to generate a code which indicates the 3D printer the info to print the part. Generate this code is not an easy task and it used depends on the type of 3D printer which is going to be used.

In this case is going to be use an **Original Prusa i3 mk3s &mk3s+ 3D printer**, which belongs to the FDM family, what means that it works depositing melted material in a pre-determined path layer by layer. The main reason for using this 3D printer is because the parts are going to be made by PLA plastic, which is perfect to this 3D printer. Besides this 3D printer is available to use in the department of mechanical engineering at CTU.

Picture 32. Original Prusa i3 MK3S & MK3S+ 3D printer

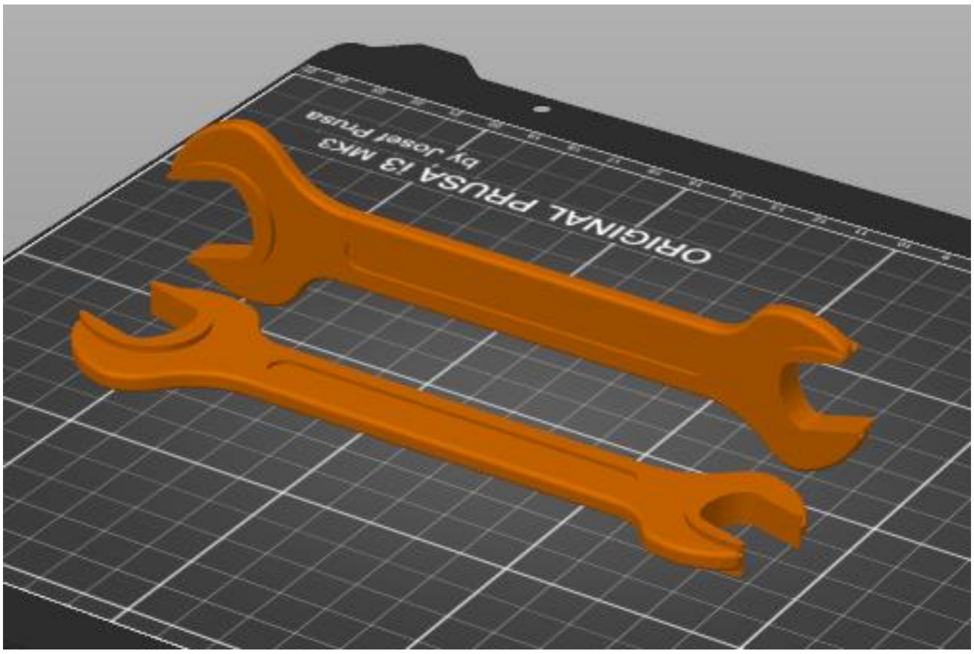
This 3D printer has its own app to generate all the printing codes. This app is called PrusaSlicer is defined as an open-source, feature-rich, frequently updated tool that contains everything necessary to export the perfect print files for the original Prusa 3D printer.

4.1.5.2. **3D printing process**

The complete manufacturing process is defined by following some steps:

1- Import the 3D model of the part and ubicate it on the printer table. Also the print orientation of the part must be decided, because the internal structure will depends on it and the behavior against forces may vary.

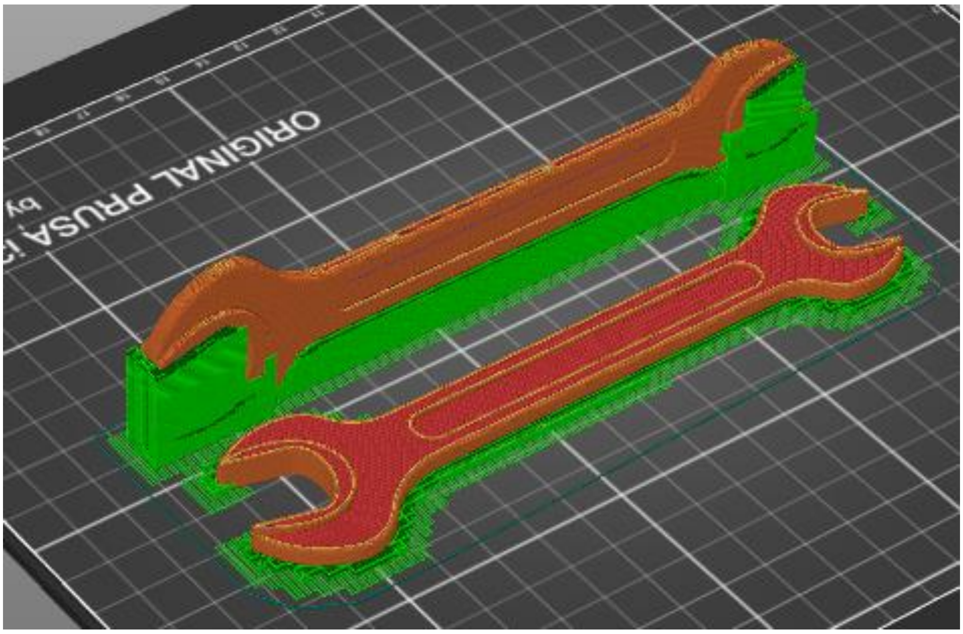
In this case it was decided to print two fixed wrenches, one with vertical and other with horizontal printing orientation. Both parts were ubicates in the same print table in order to accelerate the process.



Picture 33. Preparation to print with the disposition of the parts

2- Determine the printing supports necessaries to print the part. These supports depend on the complex of the part shape. There exist different orientations rules of how and where is necessary to put supports and the own software offers different automatic alternatives. However, to ensure that the support is correct, an option *called paint on supports* is used to distribute the supports manually along the part.

In this case, following the design rules described previously in this document, the supports are placed manually on the face which is in contact with the print table and in the areas where are cantilevered, like in the gap of the mouths.



Picture 34. Fixed wrenches with supports (PrusaSlicer)

3- Generate the printing code with the software and send it to the 3D printing to start the printing process.
4- Printing process takes 4h 26min.

Picture 35. Fixed wrenches with supports (Printed)

5- When the printing has finished is necessary to do a postprocessing task in order to eliminate all the supports from the parts. In this case, as is made by PLA plastic, this task can be easily done manually.

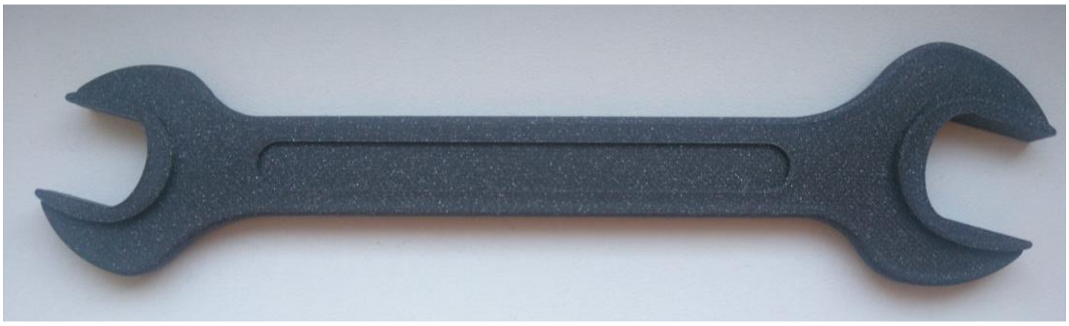
Picture 36. Postprocessing result

4.1.5.3. **Results**

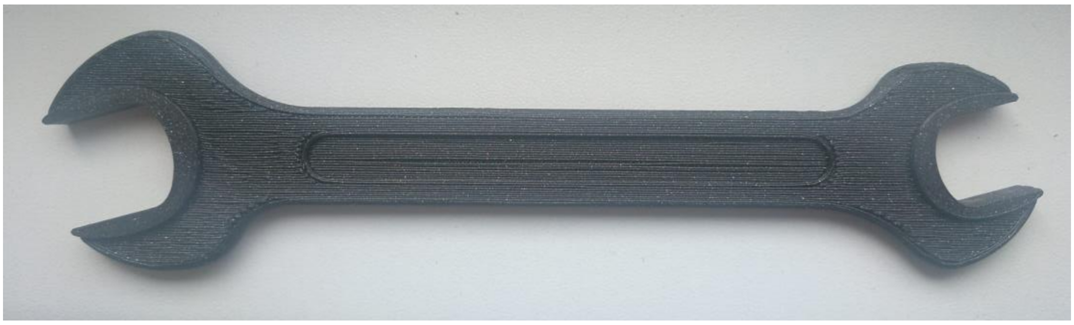
After the postprocessing task the parts obtained have different characteristics:

- Horizontal

The face which has been in contact with the supports and the printer table has a worst surface finish and is rough. However the rest of the part and specially the mouth surfaces are smooth, which is perfect for this kind of tools because the measures are used to be very precise.



Picture 37. Surface smooth of the horizontal orientation part



Picture 38. Surface rough of the horizontal orientation part

Comparing *Picture 37* and *Picture 38* is easy to see the difference surface finish obtained.

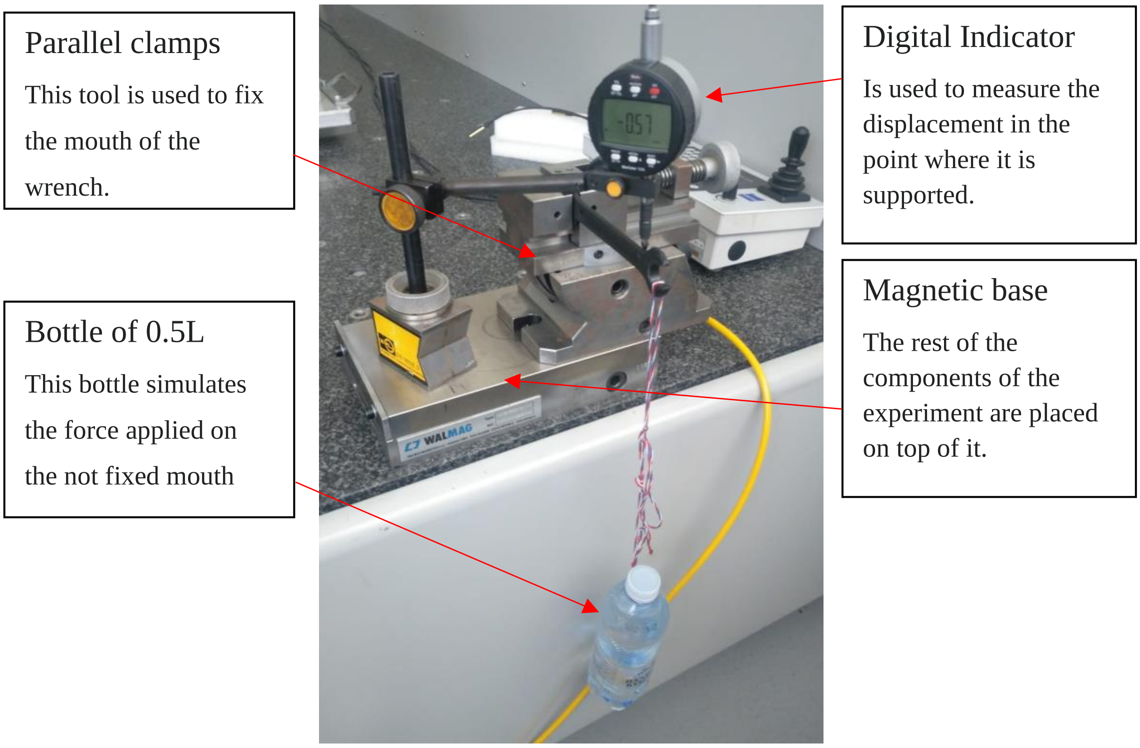
- Vertical

Although there are less area in contact with the printer table than in the horizontal case, is needed more supports due to the cantilevers of the mouths. The body has a very good surface finish, however one of the mouth surfaces is rough due to the supports.

Picture 39. Surface rough of the mouth of the vertical orientation part

4.1.6. **Experiment**

To complete the analysis of the original fixed wrenches, the manufactured parts were subjected to an experiment. This experiment consists on study the displacement resistant of the parts when a force is applied on them. To do that it has been used the following elements:



Picture 40. Elements of the experiment

With everything positioned correctly the experiment starts. Each of the parts of the original fixed wrench manufactured, is evaluated in two different positions alternatively. In this way, starting from a resting position, the force is applied for 10 seconds, that is to say, the 0.5 L bottle is hung from the opposite mouth for 10 seconds and the deformation is measured with the digital indicator. Then the load of the bottle is removed during next 10 seconds and the recovery of the deformation is measured. This is repeated five times for each mouth of the part fixed and all data are collected in the following tables.

- Mouth of 17mm fixed

HORIZONTAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,07	-0,07	-0,07	-0,07
Final deformation (mm)	-0,57	-0,58	-0,58	-0,58	-0,57
Deformation (mm)	0,57	0,51	0,51	0,51	0,50
VERTICAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,05	-0,06	-0,07	-0,07
Final deformation (mm)	-0,47	-0,49	-0,49	-0,5	-0,5
Deformation (mm)	0,47	0,44	0,43	0,43	0,43

Table 3. Experiment results mouth of 17mm fixed

- Mouth of 14mm fixed

HORIZONTAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,22	-0,24	-0,27	-0,27
Final deformation (mm)	-0,77	-0,78	-0,8	-0,8	-0,8
Deformation (mm)	0,77	0,56	0,56	0,53	0,53
VERTICAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,25	-0,28	-0,29	-0,29
Final deformation (mm)	-0,76	-0,78	-0,8	-0,79	-0,8
Deformation (mm)	0,76	0,53	0,52	0,5	0,51

Table 4. Experiment results mouth of 14mm fixed

Making a comparation between the results of the experiment and the analysis of deformation done by simulation (Page 24), it can be determined that both are quite similar because in all cases the deformation is < 1mm and the maximum values are even lower. So this indicates that are correct and that this result can be compared with those of new designs.

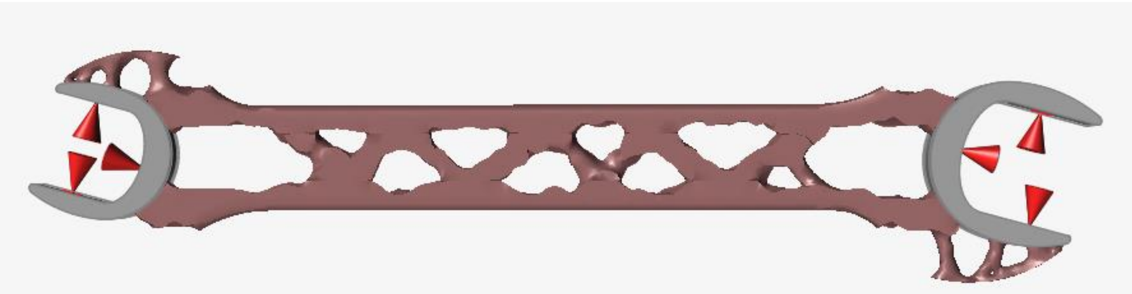
Also comparing the printing orientations, it can be seen that there are not many differences between each other. Is true that in both cases the deformation is lower in the vertical orientation. However the difference is not enough to say that the vertical orientation is better. So as a conclusion, although the vertical orientation has better results, it can be assumed that the orientation do not affect significantly in the results.

4.2. New Design

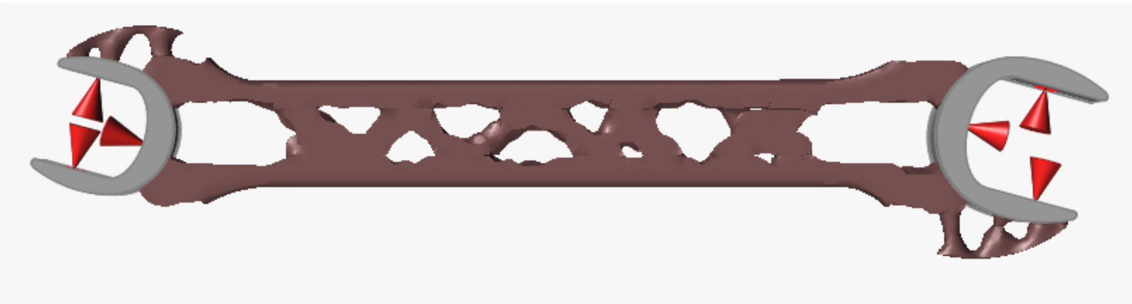
4.2.1. Topology Optimization

4.2.1.1. Optimization simulation

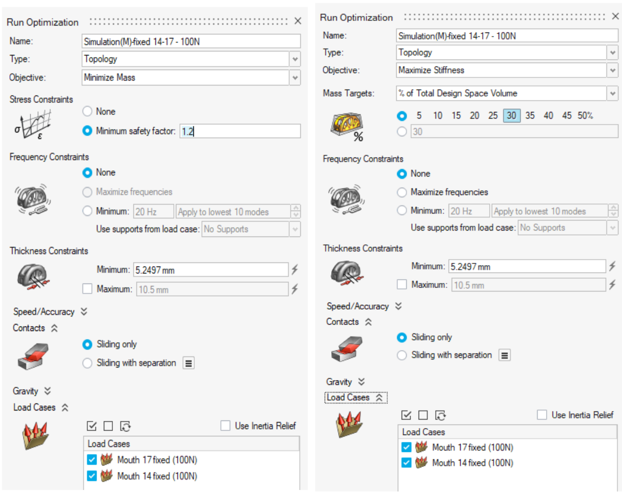
With the software Altair Inspire different optimizations can be applied to the part. To do the Topology Optimization the program has two different options: minimize the mass or maximize stiffness. For this part both optimizations are interesting, so both cases are analyzed and the results are:



Picture 41. Minimize mass



Picture 42. Maximize stiffness



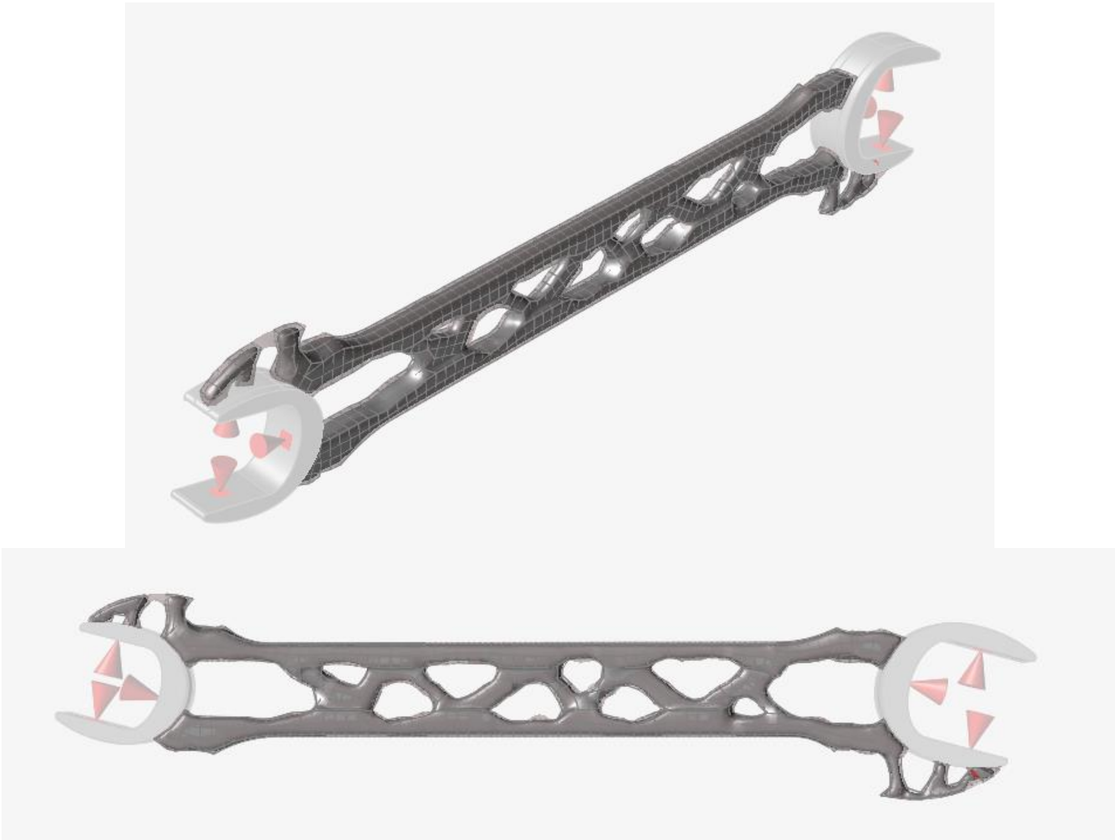
Picture 43. Configurations

4.2.1.2. Modeling process

As it is showed in the pictures, both results are very similar, so they are taken as the start point of the redesign.

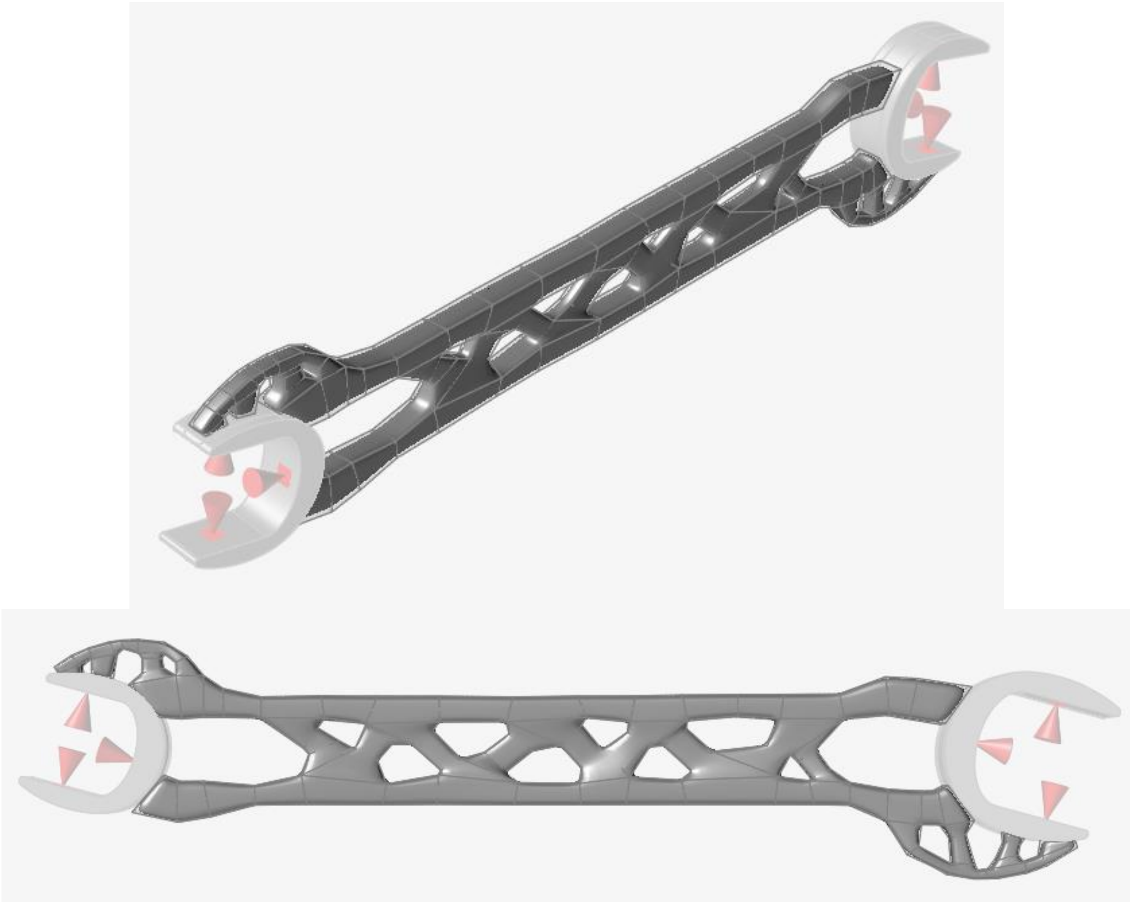
Using Altair Inspire is possible to obtain a solid made with the shape of the optimization results with different options:

- FIT POLYNURBS, this tool generates automatically a solid with the shape of the optimization results. However the problem is that it generates a lot of small solid boxes whose make the part hard to edit.



Picture 44. Reconstruction using FIT POLYNURBS

- WRAP POLYNURBS, with this tool the solid boxes are modeled manually following the shape of the optimization results. The problem is that the model of the hole part must be modeled solid box by solid box, which means that it required a lot of time depends of the complexity of the part. However the use of this tool offers more capacity for free modeling.

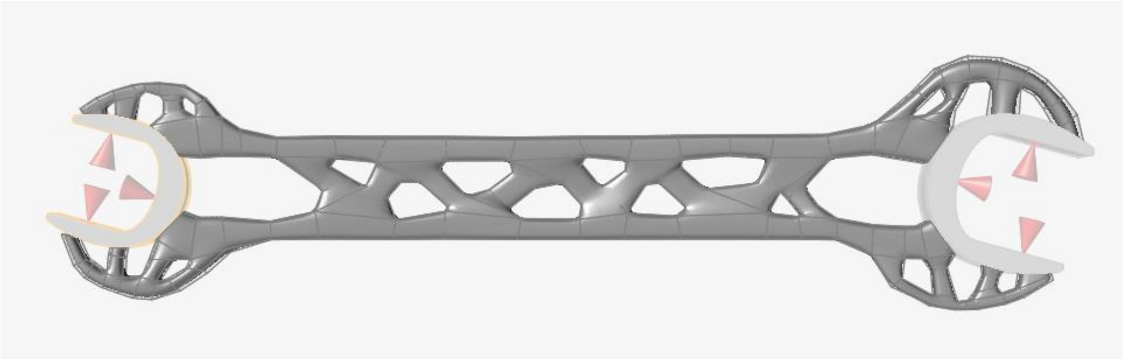


Picture 45. Reconstruction using WRAO POLYNURBS

Comparing the solids obtained with both tools, it was decided to keep on modeling only with Wrap, because the surfaces are smoothy and the part is more editable, which is perfect for futures changes.

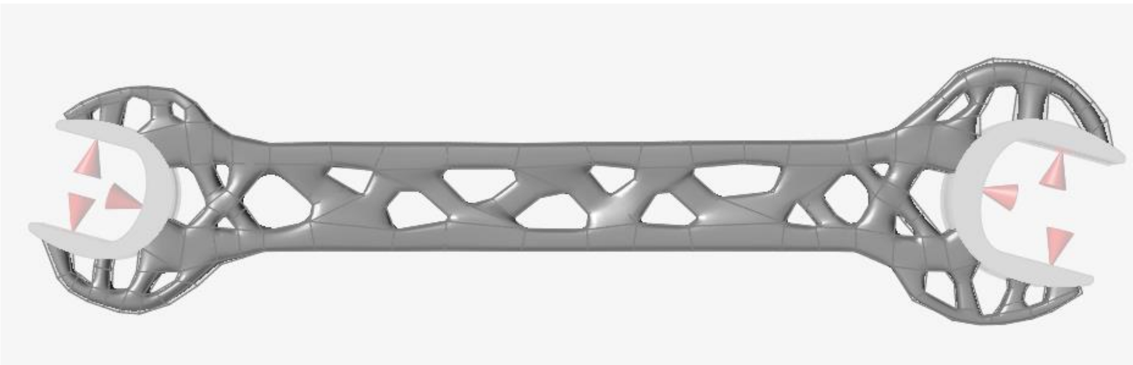
4.2.1.3. First prototype

Starting with the model obtained with Topology Optimization and keep on working to complete the shape of the fixed wrench, the result obtained is:



Picture 46. First prototype design 1

To avoid problems between the mouths and the body, some supports are added to reinforce the areas:



Picture 47. First prototype design 2

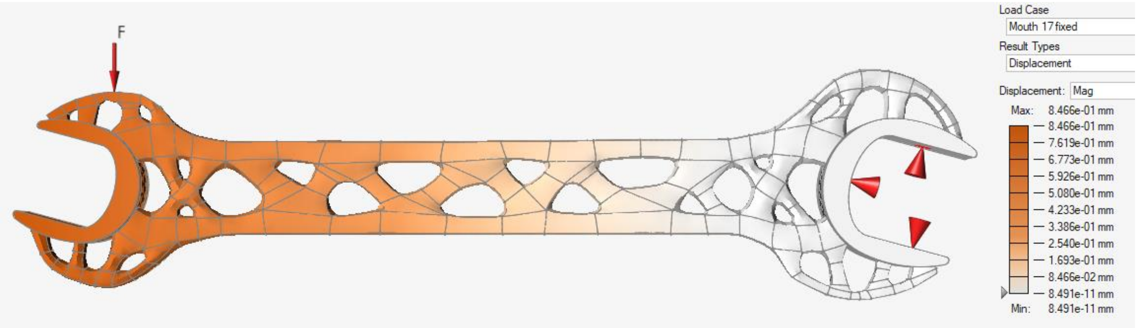
4.2.1.3.1. Analysis

As it have been done for the original fixed wrench, a complete analysis of the first prototype is done to obtain its properties.

❖ CASE 1: The mouth of 17 mm is fixed and a force of 5 N is applied over the other mouth.

- Displacement results:

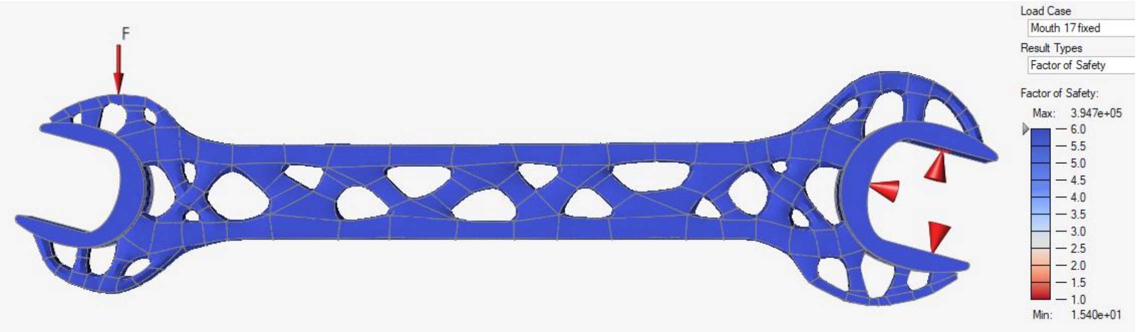
As in the original part, the maximum displacement appears in the opposite mouth, where the force is applied. Comparing both result the displacement is 0.1 mm higher in this case, but its value is < 1mm, so the part is still highly resistant.



Picture 48. Displacement

- Safety factor:

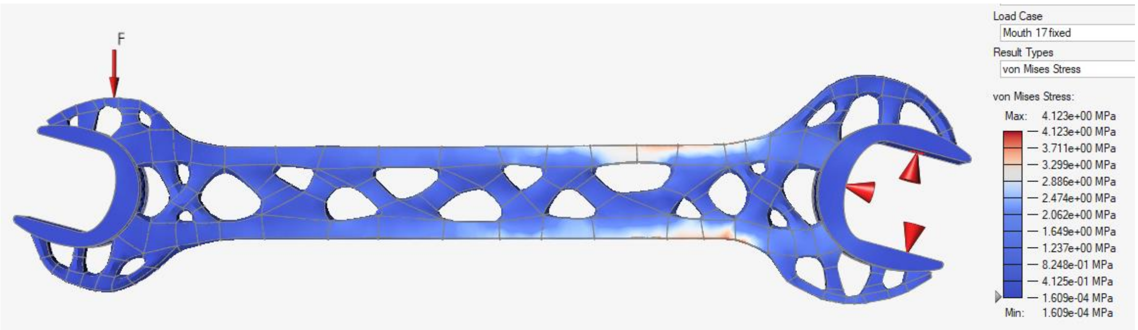
As in the original fixed wrench, the hole part has the same blue color, which means that the factor of safety is ≥ 6 in all the points of the part.



Picture 49. Safety factor

- Von Mises stress:

The critical area appears in the connection between the body of the tool and the mouth fixed because it suffers from traction and compressive forces. Although in this case the area who suffer is bigger, it is also more evenly distributed and the maximum value is still around 4 MPa, which is bearable.

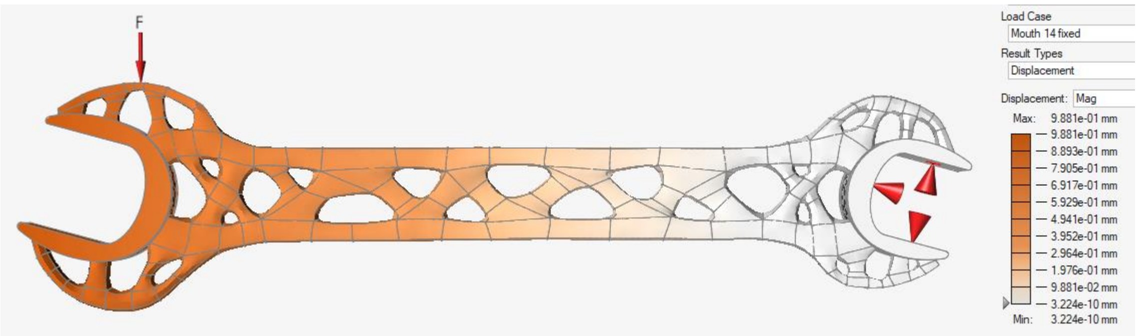


Picture 50. Von Mises stress

❖ <u>CASE 2</u>: The mouth of 14 mm is fixed and a force of 5 N is applied over the other mouth.

- Displacement results:

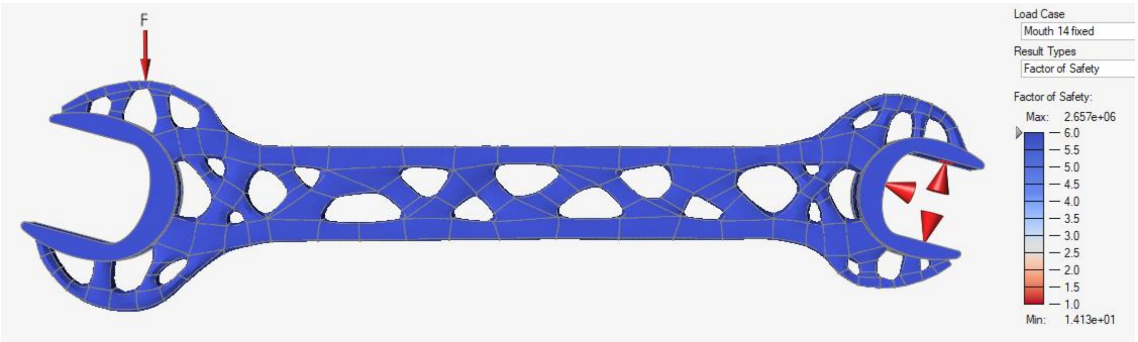
In this case occurs the same than in the other mouth, comparing the results with the original part, the maximum displacement is 0.1 mm higher, but its value is < 1mm, so the part is still highly resistant.



Picture 51. Displacement

- Safety factor:

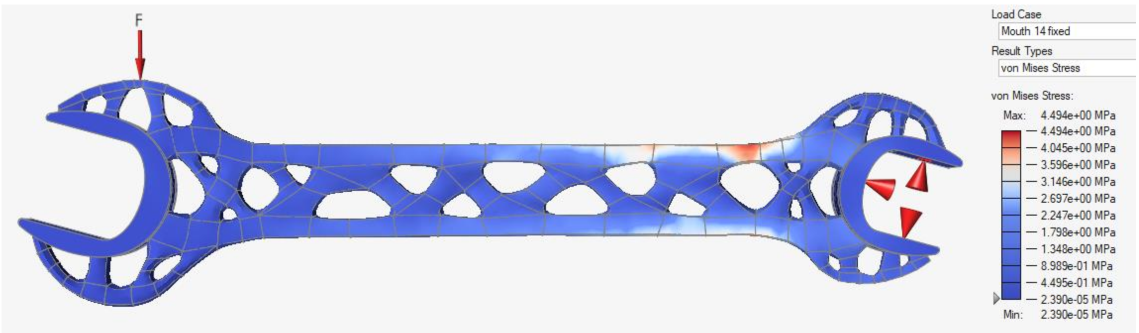
Despite of have higher displacement results, the hole part has the same blue color, which means that the factor of safety is ≥ 6 in all the points of the part, so is correct to assume it.



Picture 52. Safety factor

- Von Mises stress:

As in the CASE 1, the critical area appears in the connection between the body of the tool and the mouth fixed because it suffers from traction and compression forces, however in this case the area who suffer is bigger and specially in the area which is working in traction. Despite of that, the values are quite similar and they are still very far away from the broken limit.

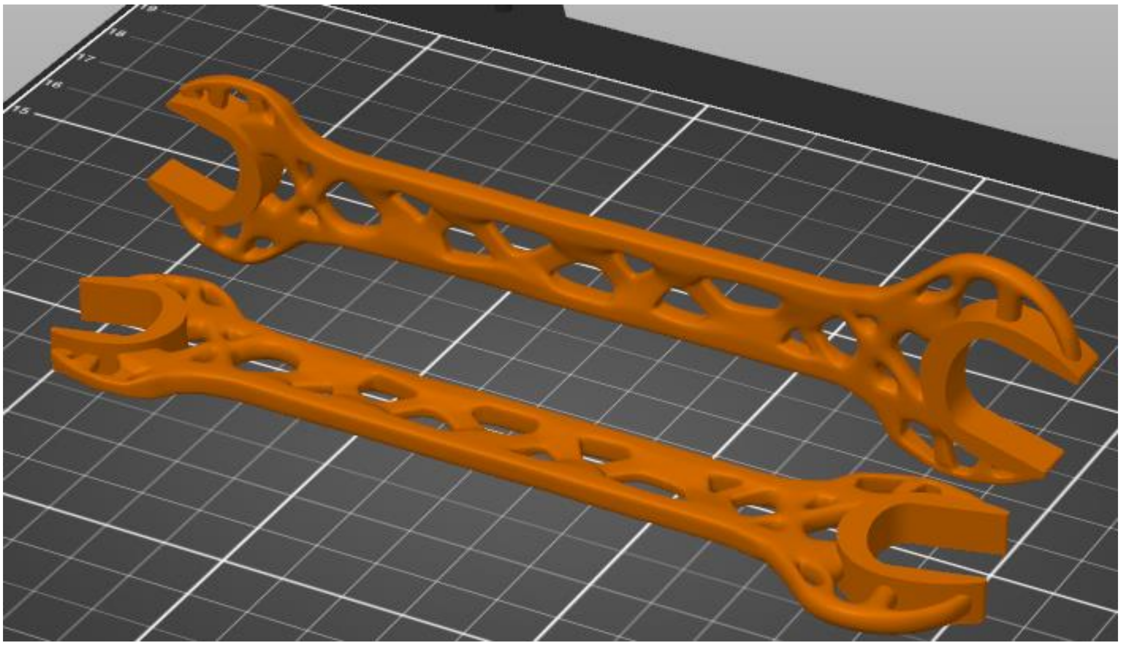


Picture 53. Von Mises stress

4.2.1.3.2. 3D printing process

To manufacture this prototype the same steps as in the original one has been followed:

1. Import the 3D model of the part and ubicate it on the printer table and determine the print orientation of the part. As two orientation want to be compared, two parts with the same design are manufactured and are distributed on the same printing table to accelerate the process.



Picture 54. Preparation to print with the disposition of the parts

2. Determine the printing supports necessaries to print the part. In this case it looks like the supports must be more complex than in the original part, however the same supports are required.

   This is because the holes which has the body of this new design are not big enough to require from more supports according with the rules described previously in this document. In the design rules it has been described that when the transition of the shape is continue with concave or convex shape, the part stands on its own, and this is what occurs in this case.

Picture 55. Fixed wrenches with supports (PrusaSlicer)

3. Generate the printing code with the software and send it to the 3D printing to start the manufacturing process.
4. Printing process takes 4h 54min.
5. Postprocessing. Removing all the support to obtain the final parts.

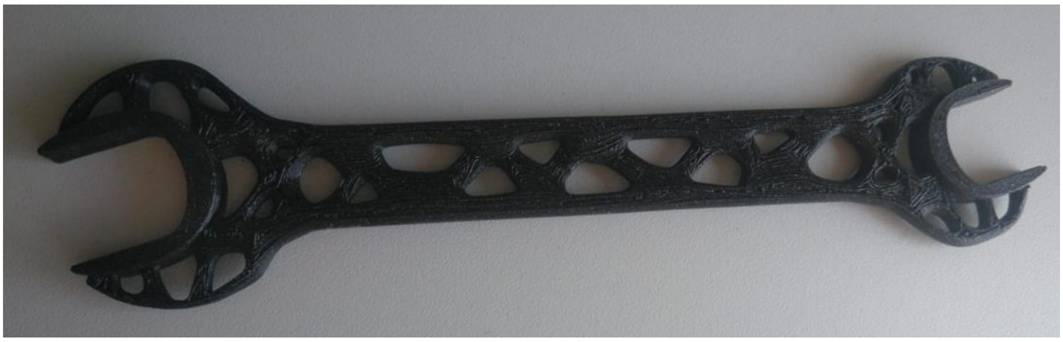
4.2.1.3.3. Results

After the postprocessing task, the parts obtained have different characteristics:

- Horizontal

The face which has been in contact with the supports and the printer table has a worst surface finish and is rough. However the mouth surfaces are smooth, which is perfect for this kind of tools because the measures are used to be very precise.

Picture 56. Surface smooth of the horizontal orientation part



Picture 57. Surface rough of the horizontal orientation part

- Vertical

With this orientation the connections have had some problems during the printing process and its quality is quite bad, which can affect directly to the properties of the part. These problems are due to a rough connection between the body and the mouths, and this causes the finish of these areas to be of poor quality.

Also, although the rest of the body is smooth, the mouth surfaces are rough due to the supports.

Picture 58. Low quality of the connections and rough surface in the mouth

- **Experiment**

Repeating the same experiment done for the original fixed wrench the results obtained are:

- Mouth of 17 mm fixed

HORIZONTAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,05	-0,04	-0,06	-0,05
Final deformation (mm)	-0,69	-0,7	-0,72	-0,71	-0,71
Deformation (mm)	0,69	0,65	0,68	0,65	0,66
VERTICAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-1,79	-1,96	-1,99	-2,06
Final deformation (mm)	-3,79	-3,96	-3,87	-4,08	-3,92
Deformation (mm)	3,79	2,17	1,91	2,09	1,86

Table 5. Experiment results mouth of 17mm fixed

- Mouth of 14 mm fixed

HORIZONTAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,12	-0,12	-0,12	-0,12
Final deformation (mm)	-0,81	-0,81	-0,82	-0,82	-0,86
Deformation (mm)	0,81	0,69	0,7	0,7	0,74
VERTICAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,61	-0,62	-0,62	0,63
Final deformation (mm)	-1,27	-1,29	-1,3	-1,31	-1,32
Deformation (mm)	1,27	0,68	0,68	0,69	1,95

Table 6. Experiment results mouth of 14mm fixed

As it can be seen these results are not as good as expected especially in the vertical orientation part. There are a huge difference between the deformations obtained in the simulation and the obtained in the real experiments, which indicates that something is wrong.

This may be because, during the printing process, there have been some complications in the connections and the finish of the part has differences respect to the model design.

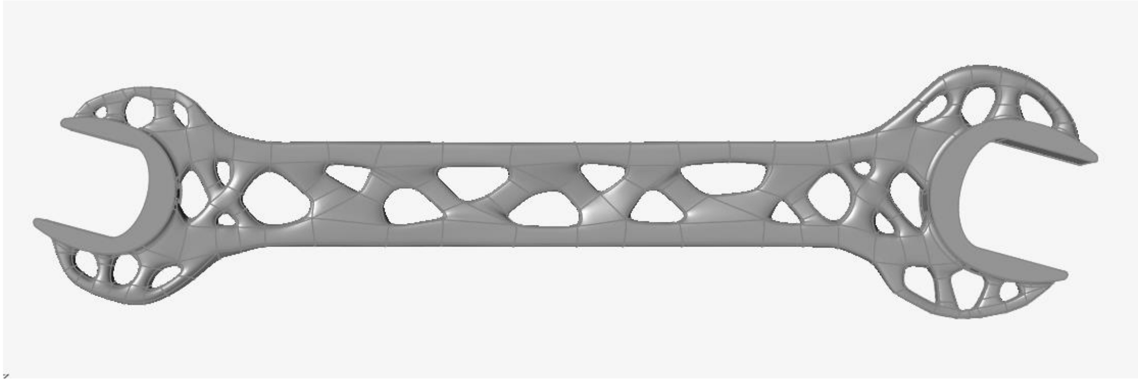
This kind of problems are important too, because although the model design of the part is good, the obtained part is not. This shows the importance of having in mind the manufacturing process during the design process to avoid problems and to improve the design.

4.2.1.4. Final design

4.2.1.4.1. Changes realized

After having studied the first prototype, there are some important changes needed to improve the final product.

The main problem has been the abrupt connections between along all the part without rounding them to facility the printing process and to improve the properties of the fixed wrench. In this way, apart of change some shapes to do the design smoother, all the connections of the structure have been rounded and specially in the connections between the body and the mouths.



Picture 59. Final design

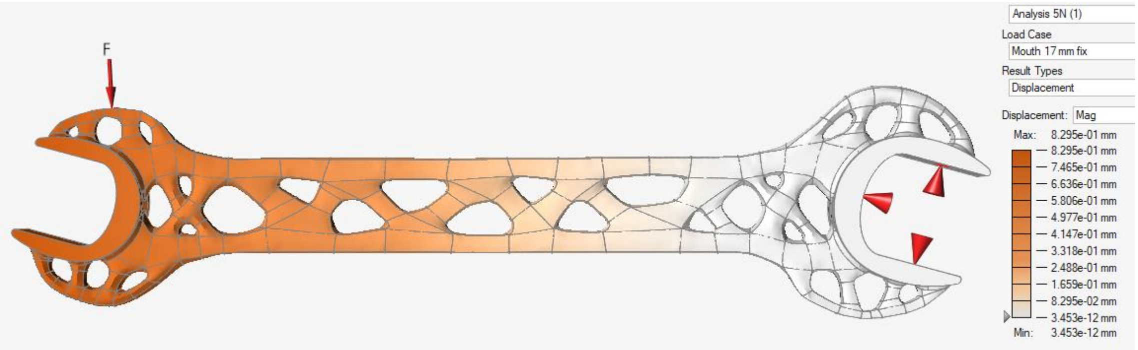
4.2.1.4.2. Analysis

Although the changes are minimums, the analysis simulating with Altair Inspire has been repeated:

❖ CASE 1: The mouth of 17 mm is fixed and a force of 5 N is applied over the other mouth.

- Displacement:

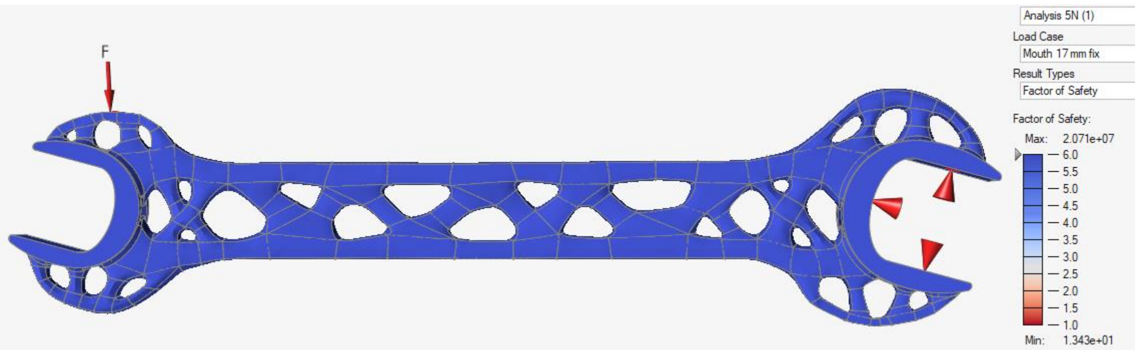
As with the rest designs, the maximum displacement appears in the opposite mouth, where the force is applied. In this case occurs the same than in the first prototype that, comparing with the displacement of the original part, now is 0.1 mm higher in this case, but its value is < 1mm, so the part is still highly resistant.



Picture 60. Displacement

- Safety factor:

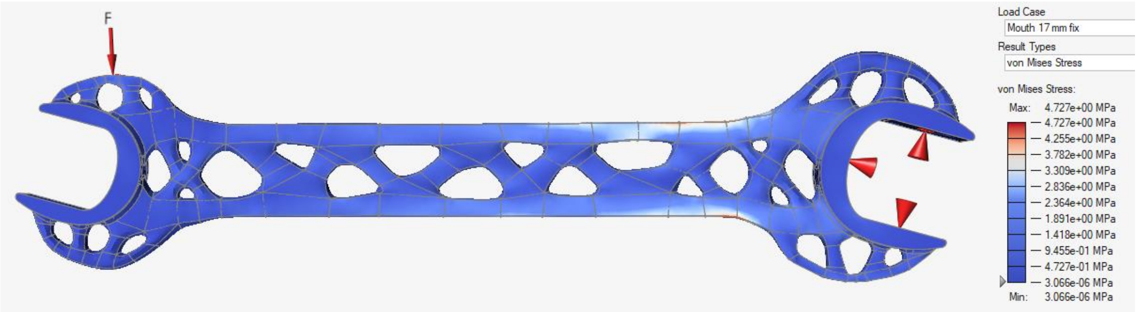
As in the original fixed wrench, the hole part has the same blue color, which means that the factor of safety is ≥ 6 in all the points of the part.



Picture 61. Safety factor

- Von Mises stress:

The critical area appears in the connection between the body of the tool and the mouth fixed because it suffers from traction and compression forces. In this case it has been possible to reduce the affected area compared to the first prototype and the maximum value is still around 4MPa, which is bearable.

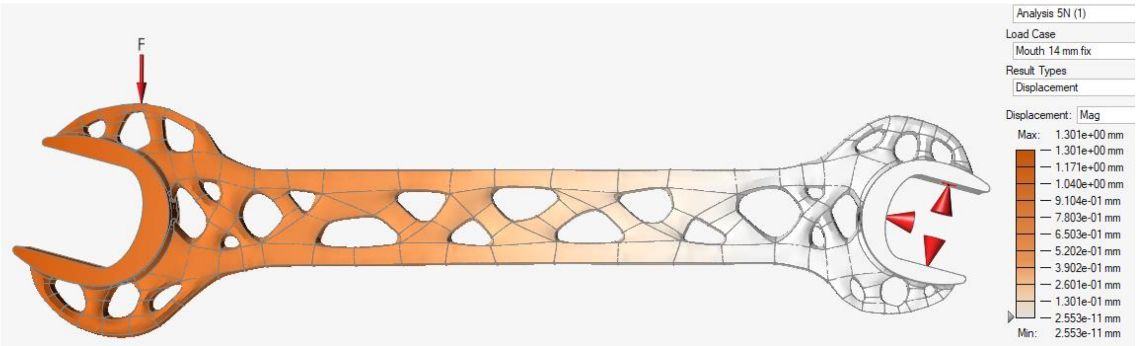


Picture 62. Von Mises stress

❖ <u>CASE 2</u>: The mouth of 14 mm is fixed and a force of 5 N is applied over the other mouth.

- Displacement:

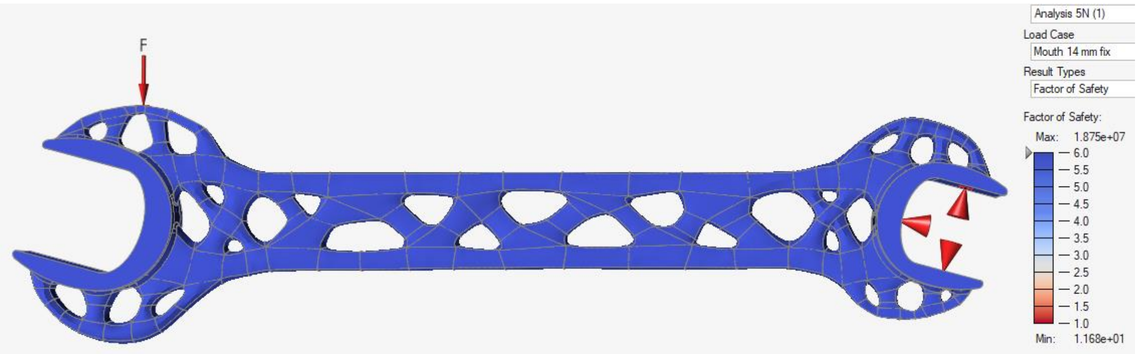
In this case it can be seen that the maximum displacement is > 1 mm and, although is considerable, it will be assumed as enough resistant to achieve with the operations what it has been designed for.



Picture 63. Displacement

- Safety factor:

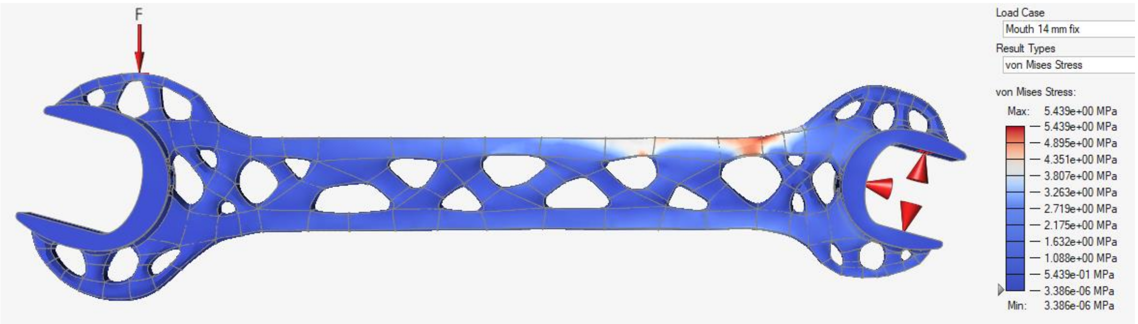
Despite of have higher displacement results, the hole part has the same blue color, which means that the factor of safety is ≥ 6 in all the points of the part, so is correct to assume it.



Picture 64. Safety factor

- Von Mises stress:

In this case occurs the same than in the first prototype and the area affected is the connection between the body and the mouth fixed because is working in traction. Although the maximum value is higher, it can be assumed because is still far away from the broken limit.

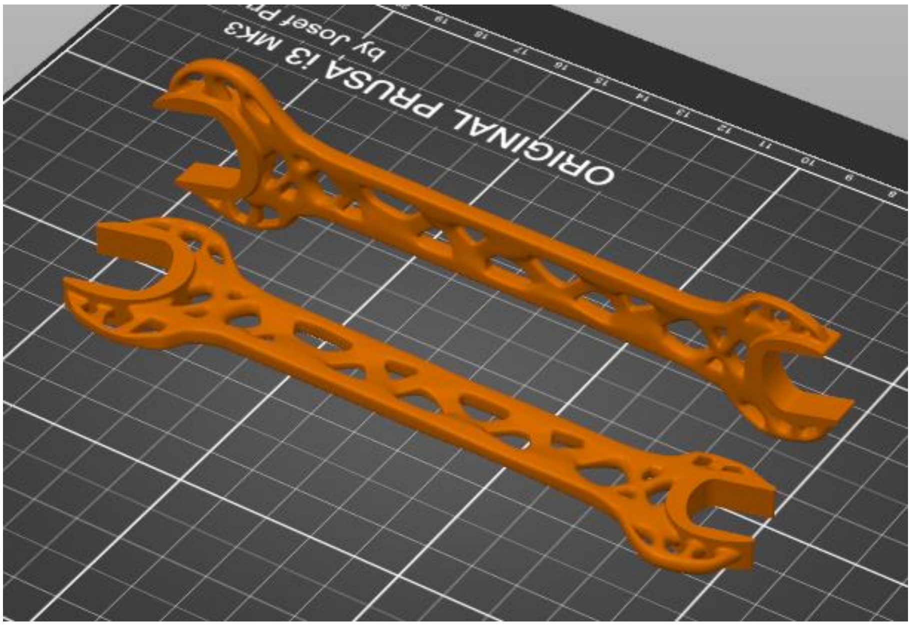


Picture 65. Von Mises stress

4.2.1.4.3. 3D printing process

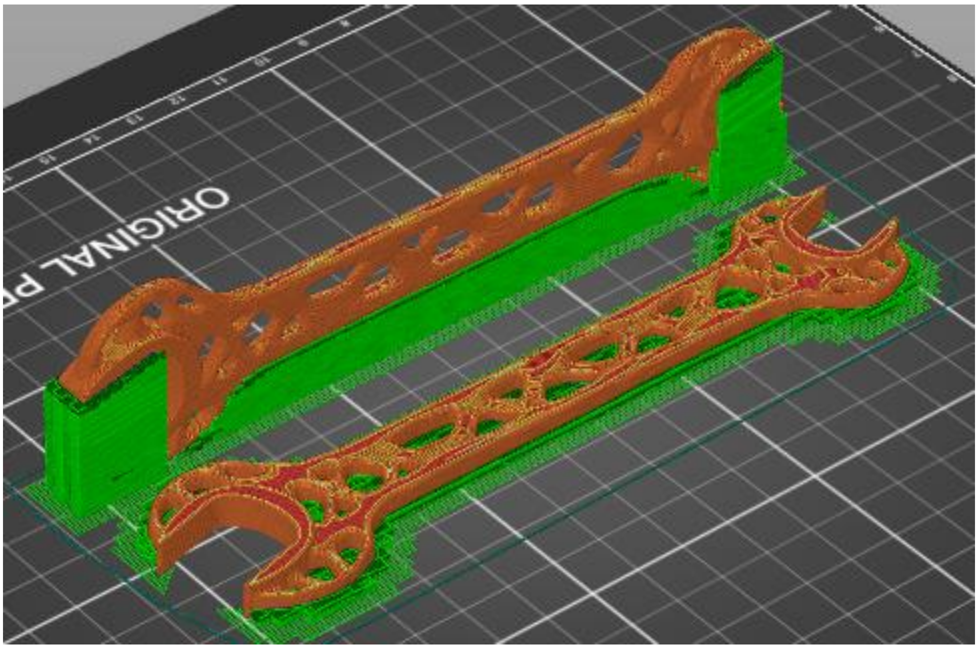
With the changes improved, the printing of the parts with the final has been easier due to changes realized. The same steps than in before cases have been followed:

1. Import the 3D model of the part and ubicate it on the printer table and determine the print orientation of the part. As two orientation want to be compared, two parts with the same design are manufactured.



Picture 66.. Preparation to print with the disposition of the parts

2. Determine the printing supports necessaries to print the part. These supports depend on the complex of the part shape and although the shape of this design is more complicated, the supports are still the same than the original. That is because the holes which has the body of this design are not enough bigger to requires supports and the part can be printed without any problem.



Picture 67. Fixed wrenches with supports (PrusaSlicer)

3. Generate the printing code with the software and send it to the 3D printing to start the manufacturing process.
4. Printing process takes 4h 52min.

Picture 68. Fixed wrenches with supports (Printed)

5. Postprocessing. Removing all the support to obtain the final part.

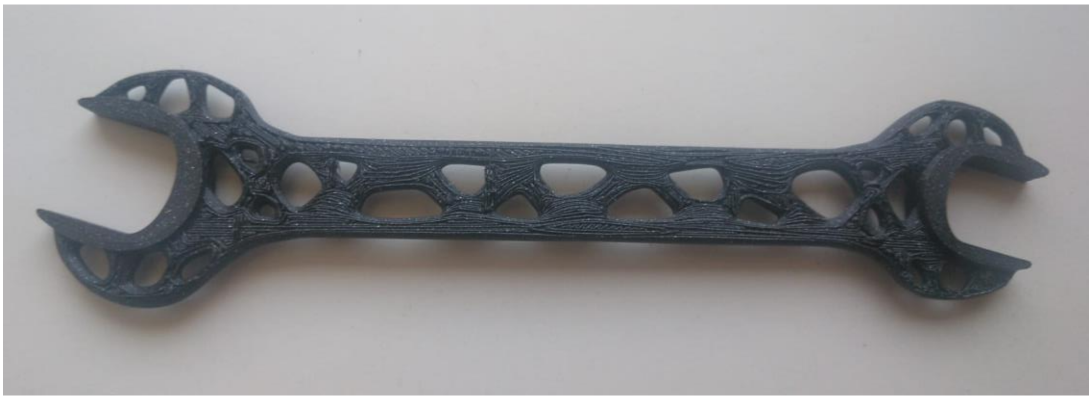
4.2.1.4.4. Results

The result obtained in these designs have the same characteristics than in the first prototype. However the manufactured parts obtained have more quality and after the postprocessing task the parts obtained have different characteristics:

- Horizontal

The face which has been in contact with the supports and the printer table has a worst surface finish and is rough. However the mouth surfaces are smooth, which is perfect for this kind of tools because the measures are used to be very precise.

Picture 69. Surface smooth of the horizontal orientation part



Picture 70. Surface rough of the horizontal orientation part

- Vertical

In this case, as the connections have been rounded, the problems during the printing process have disappeared. The characteristic to comment is that all the body has a good finish but the mouths are a little bit rough because of the support, so it happens the same as in the part of the original fixed wrench. However in general, the part has more quality than the first prototype.

Picture 71. Rounded connections improve the quality of the part

4.2.1.4.5. Experiment

Repeating the same experiment done for the original fixed wrench the results obtained are:

- Mouth of 17 mm fixed

HORIZONTAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,1	-0,1	-0,11	-0,11
Final deformation (mm)	-0,6	-0,6	-0,61	-0,61	-0,61
Deformation (mm)	0,60	0,50	0,51	0,50	0,50
VERTICAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,05	-0,05	-0,06	-0,07
Final deformation (mm)	-0,54	-0,55	-0,56	-0,57	-0,58
Deformation (mm)	0,54	0,5	0,51	0,51	0,51

Table 7. Experiment results mouth of 17mm fixed

- Mouth of 14 mm fixed

HORIZONTAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,08	-0,08	-0,08	-0,09
Final deformation (mm)	-0,67	-0,68	-0,68	-0,69	-0,69
Deformation (mm)	0,67	0,60	0,60	0,61	0,60
VERTICAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,06	-0,06	-0,06	-0,07
Final deformation (mm)	-0,67	-0,67	-0,68	-0,69	-0,69
Deformation (mm)	0,67	0,61	0,62	0,63	0,62

Table 8. Experiment results mouth of 14mm fixed

The results obtained with the final design have sense because they are better than the obtained in the simulations, which means that the data is correct as occurs in the original fixed wrench results.

Comparting with the other designs, the results are better than in the first prototype because the deformation are lower in each case and also are similarities, and even better in one of the cases, than in the original fixed wrench. As a resume, it could be said that this design obtained is very positive for this study.

Besides comparing both orientations, both have similar deformations so it can be assumed that the orientation do not affect significantly in the results, as occurs in the original fixed wrench.

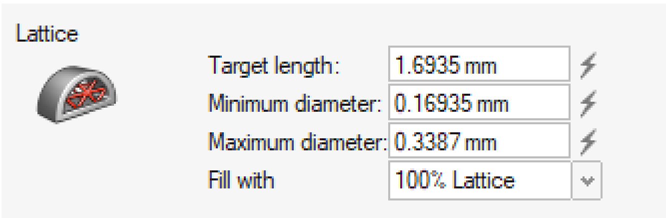
4.2.2. Lattice Optimization

4.2.2.4. Optimization simulation

Other of the optimizations available in the software Altair Inspire is the lattice structure. In this case the program optimizes the part directly by only introducing some parameters which influences significantly.

As in the Topology Optimization it can be choose the objective of the optimization between maximize stiffness and minimize mass. In this case it will be chosen the maximize stiffness option because with a lattice structure it is assumed that the weight is going to be lower than the original one, however depending of the resistance of this lattice structure, this optimization could be good or no.

Hereunder are showed some of the most important parameter that are important to change in function of the preferences of the wised result.



Picture 72. Lattice parameters

1- Target length

This parameter determines how much space will be between the lattice structure. It is complex to describe but to explain better as bigger this parameter is, the less compact the lattice structure will be.

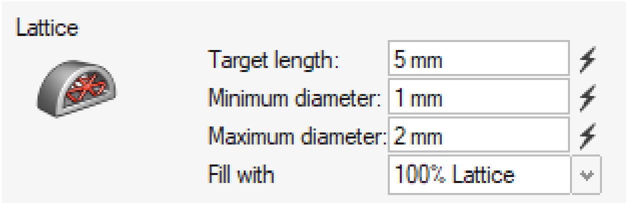
2- Minimum and maximum diameter

With these two parameters the thickness of the structure is determined with diameters between that values. These parameters also affect to the compactness of the lattice structure.

3- Percentage of lattice

The percentage of lattice determines how much of the design space is going to be filled with lattice structure. This could be useful in cases where is interesting to mix solid areas with lattice structure to reinforce the part where is necessary.

After having tested with all the combinations changing the parameters mentioned, a solution has been reached with the following configuration:



Picture 73. Lattice parameters final configuration

Picture 74. Final design

4.2.2.5. Analysis

Once the optimization is done as good enough for the study, the analysis can start:

❖ <u>CASE 1</u>: The mouth of 17 mm is fixed and a force of 5 N is applied over the other mouth.

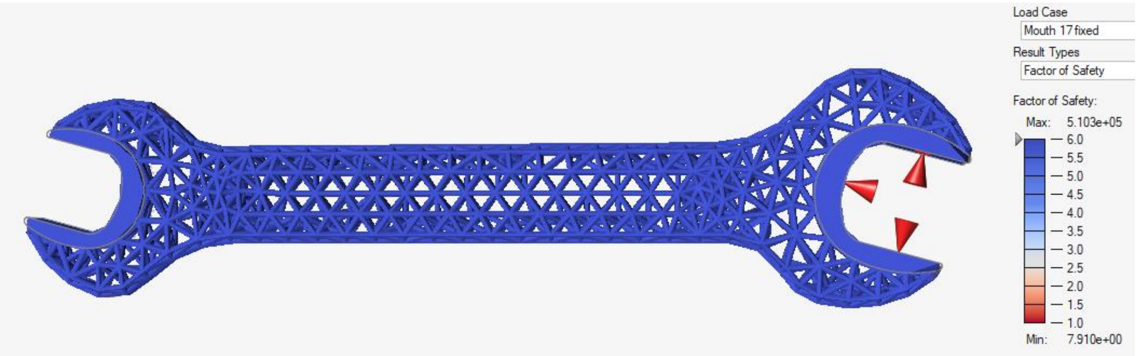
- Displacement:

As in the original part the maximum displacement appears in the opposite mouth, where the force is applied. Comparing both result the displacement is higher in this case and the maximum value is > 1mm, but as the deformation is only 0.5 mm higher, the part is assumed for being still resistant.

Picture 75. Displacement

- Safety factor:

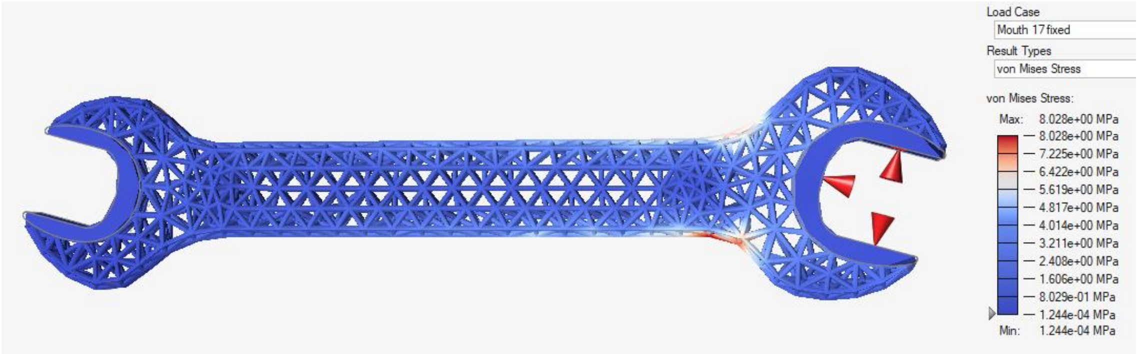
Despite of have higher displacement results, the hole part has the same blue color, which means that the factor of safety is ≥ 6 in all the points of the part, which means that is correct to assume it.



Picture 76. Safety factor

- Von Mises stress:

The critical area appears in the connection between the body of the tool and the mouth fixed because it suffers from traction and compression forces. In this case suffers more the area which is working in compression and the maximum values are around the double of the rest of designs. However the values are still far away from the broken limit, so it could be assume as bearable.



Picture 77. Von Mises stress

❖ CASE 2: The mouth of 14 mm is fixed and a force of 5 N is applied over the other mouth.

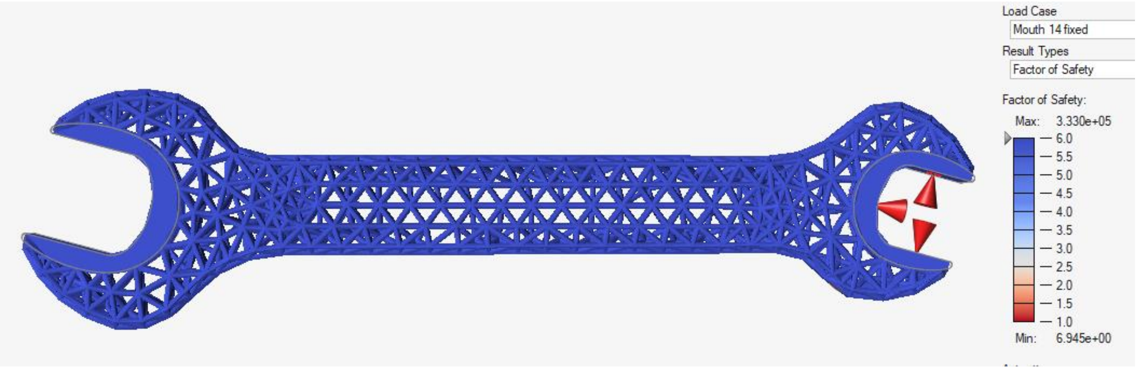
- Displacement:

As in the CASE 1 the maximum displacement appears in the opposite mouth, where the force is applied. Comparing both result the displacement is higher in this case and the maximum value is > 1mm. The deformation is around 1.8 mm, but the part is assumed for being still resistant.

Picture 78. Displacement

- Safety factor:

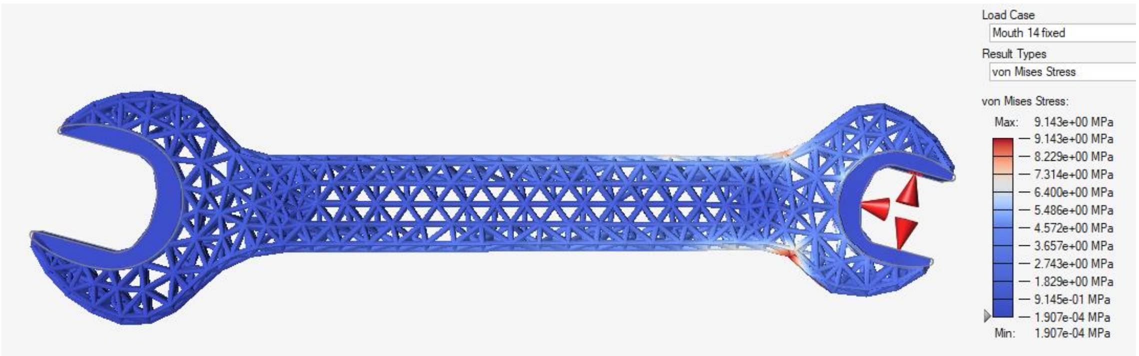
Despite of have higher displacement results, the hole part has the same blue color, which means that the factor of safety is ≥ 6 in all the points of the part, which means that is correct to assume it.



Picture 79. Safety factor

- Von Mises stress:

The critical area appears in the connection between the body of the tool and the mouth fixed because it suffers from traction and compression forces. In this case, as in the CASE 1, suffers more the area which is working in compression and the maximum values are around the double of the rest of designs. However the values are still far away from the broken limit, so it could be assume as bearable.

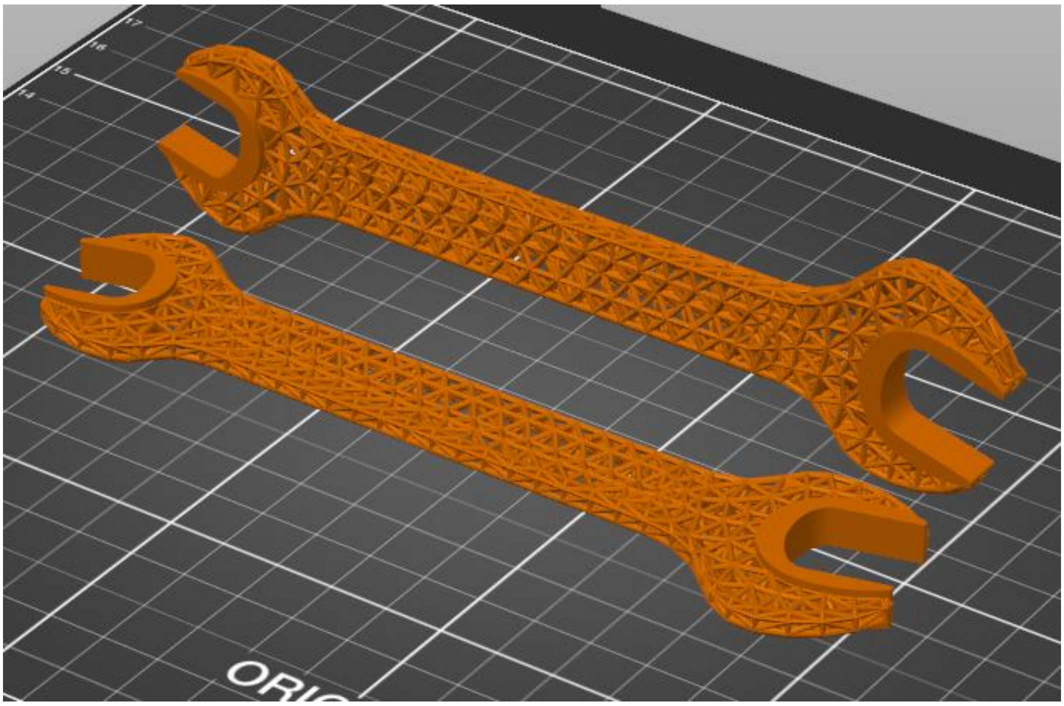


Picture 80. Von Mises stress

4.2.2.6. 3D printing process

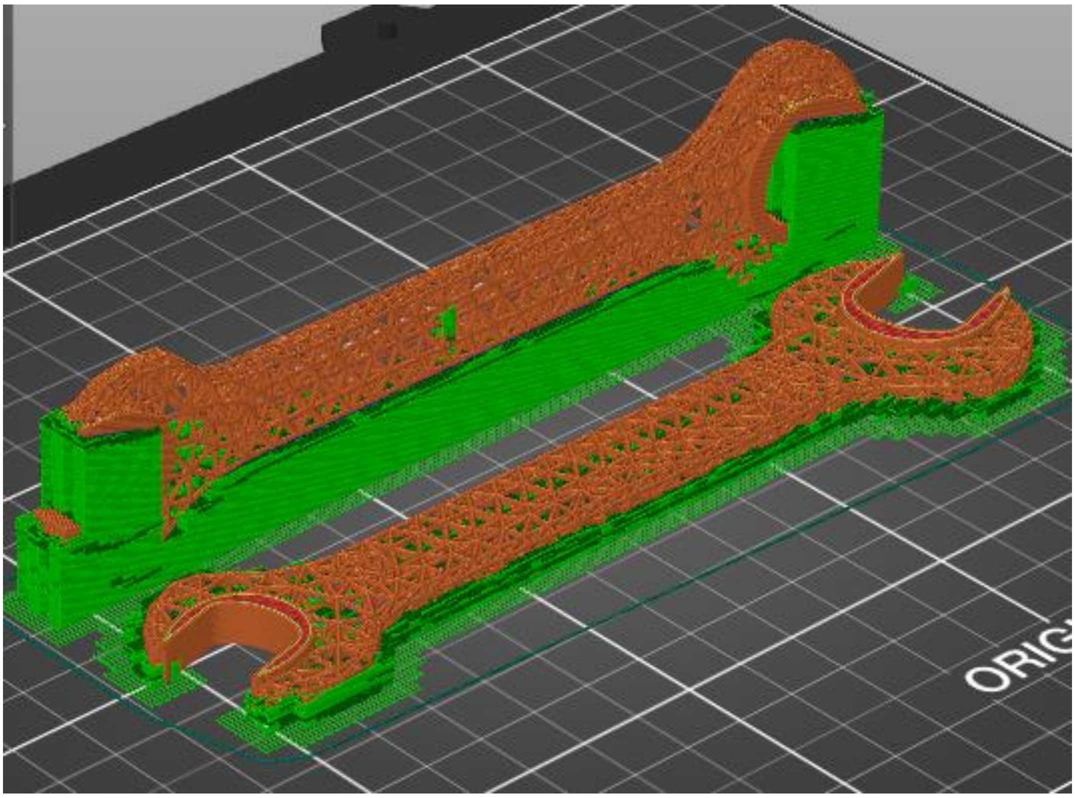
As in the topology design, after obtained the correct optimization, the same steps have been followed to print the parts with two different orientations:

1- Import the 3D model of the part and ubicate it on the printer table and determine the print orientation of the part. As two orientation want to be compared, two parts with the same design are manufactured.



Picture 81. Preparation to print with the disposition of the parts

2- Determine the printing supports necessaries to print the part. These supports depend on the complex of the part shape and although the shape of this design is more complicated, the supports are still the same than the original. That is because the holes which has the body of this design are not enough bigger to requires supports and the part can be printed without any problem.



Picture 82. Fixed wrenches with supports (PrusaSlicer)

3- Generate the printing code with the software and send it to the 3D printing to start the manufacturing process.

4- Printing process takes 9h 40min, twice as long as other designs.

5- Postprocessing necessary to remove the supports. In this case this is task is quite complicated and specially in the part with horizontal orientation. This is because, as the lattice structure is very thin, some supports are between the structure and are difficult to remove.

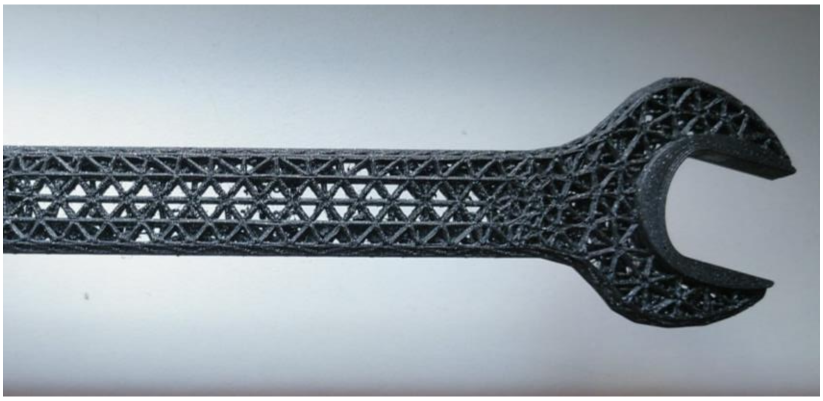
4.2.2.7. Results

After the postprocessing task the parts obtained have different characteristics:

- Horizontal

The face which has been in contact with the supports and the printer table has a worst surface finish and is rough. However in this case that surface has not too much difference respect the rest of the body. Also with this orientation, the surfaces of the mouths are smooth, which is ideal for this type of tools.

Which is important to mention is that in the horizontal orientation there are supports between the lattice structure which are almost impossible to remove. As it can be seen in the *Picture 83*, there are some areas, especially close to the mouth, where the gaps of the lattice structure are full of supports which make the part heavier.



Picture 83. Surface rough of the horizontal orientation part

- Vertical

In this case all the body has a good finish but the mouths are a little bit rough because of the support. However the important is that the lattice structure is obtained with a highly quality then in the other orientation because there are less supports between it.

Picture 84. Low quality of the connections and rough surface in the mouth

4.2.2.8. Experiment

Doing the same experiment than for the previous design the results obtained are:

- <u>Mouth of 17 mm fixed</u>

HORIZONTAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,23	-0,23	-0,24	-0,25
Final deformation (mm)	-1,49	-1,5	-1,51	-1,52	-1,52
Deformation (mm)	1,49	1,27	1,28	1,28	1,27
VERTICAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-1,1	-1,14	-1,16	-1,52
Final deformation (mm)	-2,41	-2,48	-2,54	-2,65	-3,14
Deformation (mm)	2,41	1,38	1,4	1,49	1,62

Table 9. Experiment results mouth of 17mm fixed

- <u>Mouth of 14 mm fixed</u>

HORIZONTAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,11	-0,12	-0,13	-0,13
Final deformation (mm)	-1,32	-1,33	-1,33	-1,34	-1,35
Deformation (mm)	1,32	1,22	1,21	1,21	1,22
VERTICAL ORIENTATION					
Attempt	1	2	3	4	5
Initial deformation (mm)	0,00	-0,28	-0,3	-0,3	-0,42
Final deformation (mm)	-1,44	-1,51	-1,5	-1,53	-1,54
Deformation (mm)	1,44	1,23	1,2	1,23	1,12

Table 10. Experiment results mouth of 14mm fixed

The results obtained have sense because they are better than the obtained in the simulations, which means that the data is correct as occurs in the original fixed wrench results.

Comparting with the other designs, the results are the worst, because the deformation is > 1 mm in all the cases. This is logic because the lattice structure is less resistant and this part is made 100% with this technique. However, although the results are the worst, the properties obtained shows that this design is still valid to comply with the requirements of this kind of tool.

Besides comparing both orientations, it is possible to see how in the case 1 the horizontal one has obtained lower deformations than the vertical one, but in the case 2 the results are quite similar. So it can be assumed that the horizontal orientation is better in this case, but as it is not clear enough, there is no clear evidence, so it is not possible to be sure.

5. COMPARATION

After having analyzed and studied the new designs obtained by applying optimize methods, a comparation must be done to determine if the results are as good enough to replace the original design. To do that, all the properties obtained of the different designs have been collected in the following table:

PARTS	PROPERTIES	Case 1 (17 mm fix)	Case 2 (14 mm fix)
ORIGINAL FIXED WRENCH (HORIZONTAL ORIENTATION)	Weight (Kg)	0,013484	
	Volume (mm^3)	10875	
	Max. deformation simulation (mm)	0,7189	0,844
	Mean deformation real (mm)	0,52	0,59
	Safety Factor	>6	>6
	Max. Von Mises stress (MPa)	4,047	4,647
ORIGINAL FIXED WRENCH (VERTICAL ORIENTATION)	Weight (Kg)	0,013484	
	Volume (mm^3)	10875	
	Max. deformation simulation (mm)	0,7189	0,844
	Mean deformation real (mm)	0,44	0,56
	Safety Factor	>6	>6
	Max.Von Mises stress (MPa)	4,047	4,647
TOPOLOGY OPTIMIZATION (HORIZONTAL ORIENTATION)	Weight (Kg)	0,010479	
	Volume (mm^3)	8450,7	
	Max. deformation simulation (mm)	0,8295	1,301
	Mean deformation real (mm)	0,52	0,62
	Safety Factor	>6	>6
	Max.Von Mises stress (MPa)	4,727	5,439
TOPOLOGY OPTIMIZATION (VERTICAL ORIENTATION)	Weight (Kg)	0,010479	
	Volume (mm^3)	8450,7	
	Max. deformation simulation (mm)	0,8295	1,301
	Mean deformation real (mm)	0,51	0,63
	Safety Factor	>6	>6
	Max. Von Mises stress (MPa)	4,727	5,439
LATTICE OPTIMIZATION (HORIZONTAL ORIENTATION)	Weight (Kg)	0,01045	
	Volume (mm^3)	8427,2	
	Max. deformation simulation (mm)	1,635	1,889
	Mean deformation real (mm)	1,32	1,24
	Safety Factor	>6	>6
	Max. Von Mises stress (MPa)	8,028	9,143
LATTICE OPTIMIZATION (VERTICAL ORIENTATION)	Weight (Kg)	0,01045	
	Volume (mm^3)	8427,2	
	Max. deformation simulation (mm)	1,635	1,889
	Mean deformation real (mm)	1,66	1,24
	Safety Factor	>6	>6
	Max. Von Mises stress (MPa)	8,028	9,143

Table 11. All data collected

Comparing the results, it is possible to see that the designs obtained with optimization methods can replace the original design without any problem.

The parts obtained with the Topology Optimization are a clear example of improvement. With this technique it has been possible to lighten the weight and reduce the volume of the parts while maintaining almost the same properties as the original ones. Besides the final design obtained has been created with the idea to facilitate the 3D printing process and therefore the parts manufactured are very similar to the model. With respect to orientation printing, both also have the same properties, however if one must be selected it would be the horizontal orientation. With this orientation the mouths are smooth, which is very important to this kind of tools, and as the layers are perpendicular to the force direction, it will withstand higher force values.

Parts obtained with the Lattice Optimization have not as good properties as the previous ones but are still valid to comply with the operations of the tool. With this technique it has been possible to lighten the weight and reduce the volume of the parts even more than with the other method, but in this case the parts are less resistant as it can be seen that the values of Von Misses stress are twice as high as in other designs . Between the different orientations tested the selected one will be also the horizontal because, although there are more supports between the lattice structure which are almost impossible to remove, it happens the same than with the other optimization, that the surfaces of the mouths are smooth and also the properties in this case are a little bit better.

6. CONCLUSION

Nowadays we live in a society of continuous technological advancement and product improvement that forces companies to continually reinvent themselves and their products. One of the basic concepts used in the engineering world is the looking for optimized products especially with the pursuit of lightweighting and one of the best solutions is the Structural Optimization. In this diploma thesis it has been analyzed the different techniques of Structural Optimization that exist and that are starting to be used by the companies to improve their products. As it has been mentioned, the most popular ones are: Topology Optimization, Lattice Structure Optimization and Topography Optimization. These three techniques have been developing in last few years and now there are multitude of software which incorporate them in their optimization functions, so their application is becoming standardized and in the future it will surely be a fixed step in the manufacturing process.

Moreover the triumph of these new methods is also thanks to Additive Manufacturing. There exists a symbiotic relationship which is beneficial for both parties and thank to that, its success has multiplied. In this document is discussed the different types of additive manufacturing which exist nowadays in the market, analyzing the classification of the techniques according to the way of operating and emphasizing the most used ones: the classical technique with material extrusion and the technique of vat photopolymerization, which has different types.

Although additive manufacturing let create parts with shapes which are difficult to obtain with other manufacturing process, there are still a lot of limitations that could complicate the process and that is why designers must always be aware of these limitations in order to obtain a product with the expected quality. To make the most of this technology, in this document it has been described some design rules that are vital to know for every designer which use it. Size and shape are discussed as well as the importance of the material selection, the orientation on the printing table, the colocation of supports and the postprocessing to obtain the final part.

However, as a conclusion of the additive manufacturing, it can be said that thanks to the developing of this kind of procedure more and more companies are incorporating it to their production plants because this technology allows to manufacture not only prototypes but also final products quickly, easily and cheaply.

Once a brief study of the technology which is going to be used have been done, a commonly known part, a fixed wrench, is selected to which the optimization methods can be easily applied to demonstrate its functionality. First, the original part is scanned to obtain a 3D model to work with. With it a simulation is carried out to analyze its properties when a force is applied. Then the parts are manufactured with a 3D printer and finally these parts are subjected to an experiment where a real load is applied to analyze the deformations in response to the application of a force. All this procedure is performed for the original design, for the parts obtained with topology optimization and for the parts obtained with lattice optimization, and all the data is collected to do a comparation between them.

With the results obtained it can be said that the use of optimization methods like Topology Optimization and Lattice Structure Optimization are viable because the properties of the final products are similar or even better than the original part. In this way the parts can be lightened and optimized maintaining or even improving the original properties. So it is demonstrated that the application of these optimization methods is beneficial and its use is highly recommended, especially when is combined with additive manufacturing, because this could determine a future of design and manufacturing process.

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