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Redesign of a hot-end bracket for Additive Manufacturing

Relatore:
Chiar.mo Prof. Ing. G. Belingardi

Laureando:
Pierluigi Carbonara

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Abstract

This thesis is the result of a collaboration between Politecnico di Torino, Fiat-Chrysler Automobiles and McMaster University in Hamilton (Canada).

The objective of the project was to redesign a bracket from the exhaust system of a light commercial vehicle, obtaining a new component with the same performance and the same reliability of the existing one. The new part had to be printed with the Additive Manufacturing technology known as Selective Laser Melting (SLM).

After a two-months training period in the Mirafiori plant, the project continued from September 2017 at McMaster University for six months. The research team, called Additive Manufacturing Group (AMG) and headed by Dr. Elbestawi, is operating from 2015 in various topics related with 3D printing for metals.

The dissertation opens with an overview on the exhaust system and on the consequences of the European legislation on the subject of emission control. In the second chapter the idea of Additive Manufacturing is outlined, with particular attention to the metal-based processes: the state of the art and the challenges for the future.

The third section is devoted to the most common algorithms of Topology Optimization, which was the key-method to redesign the mechanical part in question.

A description of the model of the existing bracket is included in the fourth chapter. It embraces a modal analysis, a thermal-structural analysis and a frequency response analysis. The idea was to simulate the functioning of the initial part, with the purpose of being able to validate as well the optimized one. In the subsequent chapter an illustration of some practical aspects related with Topology Optimization is provided: managing the complex geometries resulting from the calculations and preparing them for the following steps.

After the presentation of the results of the validation analyses, a detailed report of the printing process is given, with specific reference to the investigation on the optimal process parameters and on the settings of the machine.

The thesis ends with some practical considerations on the costs associated to Additive Manufacturing for metals and on the further development of this outstanding technology.

Chapter 1

The exhaust system: the state of the art

In order to understand the current organization of the exhaust system it is necessary to be aware of the timeline of the emission standards.

In the past, the emissions control in Diesel engines was realized by some actions which concerned the inside of the motor. Nowadays, for the purpose of complying with the standards, a continuous research on the exhaust-gas treatment has been carried out, with a combination of measures which affects also the devices downstream of the engine.

The European legislation

Starting from 1993 the European Union enacted progressively stringent standards. As is widely known, for Light Duty vehicles the various stages are indicated with the contraction “Euro”, followed by a gradual Arabic number (Roman numbers are used for Heavy Duty vehicles).

This gradual procedure was later corroborated from the target imposed by the Kyoto Protocol, that is to say an 8% reduction of all CO_2 emissions in all areas of Economy, compared to the 1990 levels. The controlled substances include the Carbon Monoxide (CO), the Hydrocarbons (HC), the Nitrogen Oxides (NO_x) and the particulate matter (PM).

The requirements are obviously different, depending on whether diesel or gasoline engines are considered. In the following figure it is possible to observe a general scheme of the historical evolution of the standards for Diesel cars:

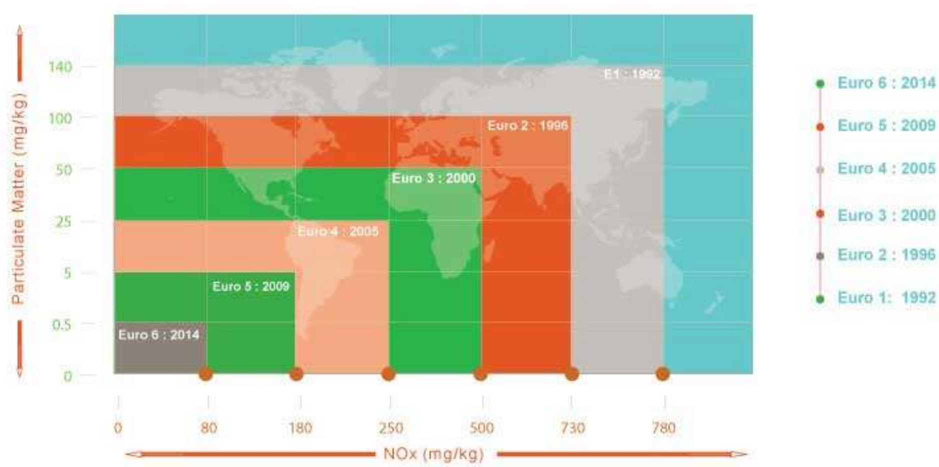


Figure 1-1 History of Euro emission standards for Diesel passenger cars.

Verifying the compliance with the emission standards is of the utmost importance. For this reason several emission test cycles, which are obviously completely standardized, are carried out, in order to represent in the best possible way the average utilization of a car in Europe.
Over time those tests have become more and more stringent, but also closer to the real situation. Since 2000 the NEDC (New European Driving Cycle) was used. It is composed by four repeated Urban Driving Cycles (UDC) and by one Extra-Urban Driving Cycle (EUDC), as it is possible to observe in the Figure 1-2:

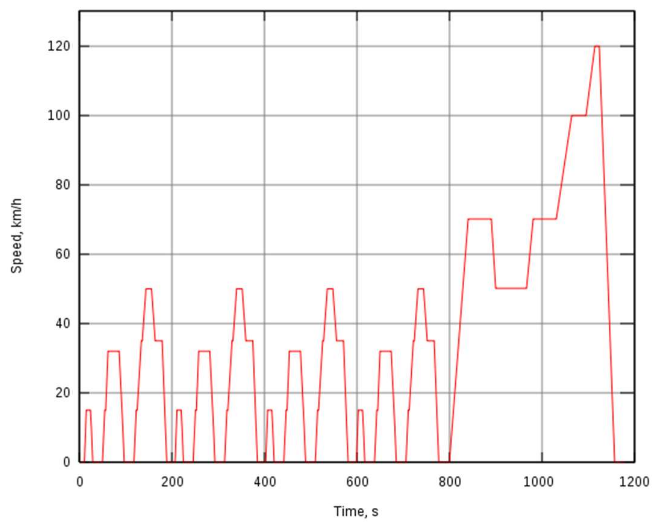


Figure 1-2: A scheme of the New European Driving Cycle (NEDC).

As an example of the requirements of the test, the vehicle must be cold (~25° C) and the cycles should be carried out on a flat road with zero wind. Nevertheless, to maintain a certain repeatability, the tests are generally performed in a laboratory, on a roller test bench.
Since the highest speed in the UDC is equal to 50 km/h, the EUDC is intended to model tougher driving conditions.
The NEDC has been severely criticized in the past years. First of all, being designed in 1997, the procedure didn't stay abreast of the new car technologies or with their actual diffusion.
For this reason, as it is possible to observe in the Figure 1-3, the NEDC has been replaced by the WLTC (Worldwide harmonized Light vehicles Test Procedure), which is supposed to be an update of the first one.

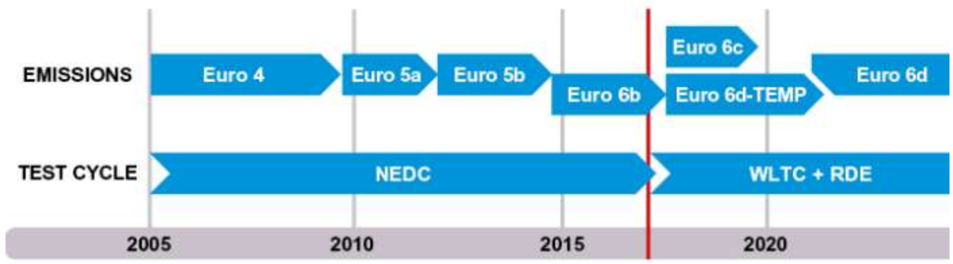


Figure 1-3: Evolution of the emission standards and of the test cycles. Source: Ricardo plc.

First of all, three different WLTC tests are available, depending on the power/weight ratio of the vehicle. In the same class, various cycles are included, having the same duration, but different shapes for speed and acceleration curves.

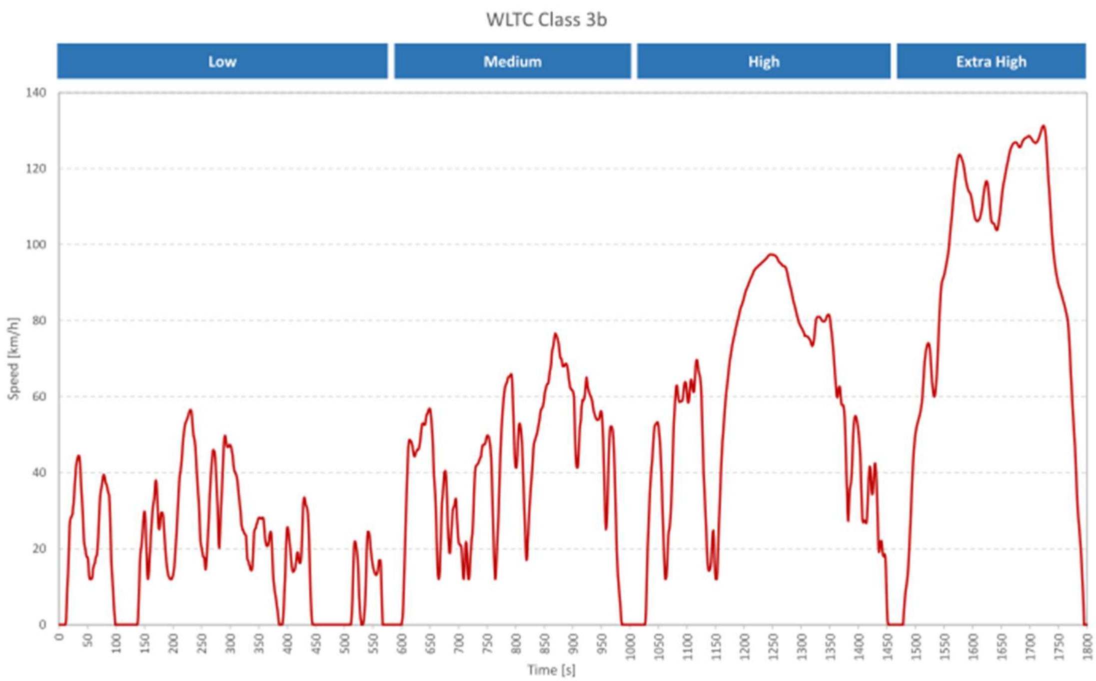


Figure 1-4: An example of a cycle of the WLTC.

As a matter of fact, the levels of CO_2 measured with the WLTP are undoubtedly higher than the previous ones. A review of the taxation levels would be therefore appropriate and advocated, with the aim of preventing a cost raising to the detriment of users.

Since the EURO 6c and 6d standards, a Read Drive Emission (RDE) check is required as well, as a completion of the laboratory tests. This is actually capable of taking into account numerous everyday life situations, which are absolutely not considered in the cycles, such as the vehicle maintenance conditions, the vehicle load, the traffic conditions, the road gradient, the weather conditions and of course, also the road type (urban, rural, highway).

The measurements are carried out with PEMS (Portable Emission Measuring Systems) devices, which can be mounted on the vehicle and can register data in real time, also using a GPS system.

Figure 1-5: A photo of a portable measuring device (PEMS).

The portable measuring equipment it is not yet standardized, therefore some differences in the results of the tests are expected from case to case. At the same time, a lower level of precision of this portable kind of instrumentation can be highlighted, compared to the laboratory equipment.

To guarantee a smooth transition towards this genre of tests, a certain initial discrepancy between the lab test and the real test will be accepted (corresponding to a conformity factor equal to 2.1 by 2019). The maximum conformity factor (CF) will be then lowered in the following years. The RDE test will be particularly challenging for the Diesel engine.

The ever more stringent requirements on emissions is one of the reasons why the Diesel engine will be abandoned by FCA by 2022, as it has just been forecast in a recent article in Financial Times[1]. This decision had been preceded by similar declarations by Toyota and Volkswagen.

The WLTC and the RDE tests have come into force on 1st September 2017.

Exhaust system overview

The exhaust system is composed of two main groups of parts, the hot end and the cold end. The first one is a set of pipes and devices which deal with the treatment of the hot exhaust gas, while it is transported towards the cold end. The key component of this system is the catalytic converter.

[1]Campbell, "Fiat Chrysler to kill off diesel in all cars by 2022", Financial Times, February 25, 2018

Instead, the cold end manages the reduction of the noise emission, through silencing features. A bigger attention will be paid to the hot end, since the redesigned bracket belongs to this system.

As already mentioned, there are several substances which need to be treated in the hot end. They include the Carbon Monoxide (CO), the Hydrocarbons (HC), the Nitrogen Oxides (NO_x) and the particulate matter (PM). The first three of them are the product of an incomplete combustion.

In the catalytic converter the oxidation and reduction chemical reactions are catalyzed with noble metals, such as Platinum, Palladium and Rhodium. In order to spread these materials over a larger surface, a washcoat is used.

The catalytic converter is composed by an internal monolith, which can be metallic or made of ceramic and it has a cell structure. In the Figure 1-6 it is possible to observe the washcoat on the metallic and on the ceramic cells:

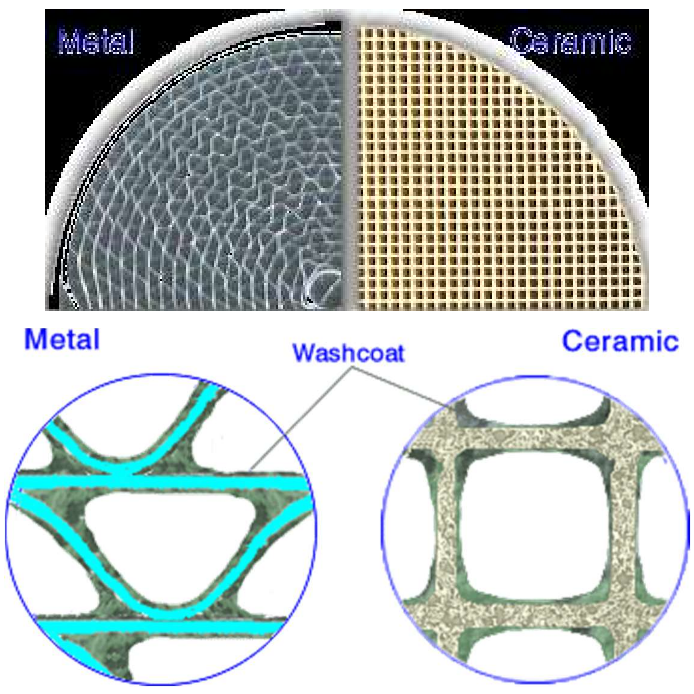


Figure 1-6: The washcoat on the inner surfaces of the honeycomb.

The high temperature in the combustion chamber is the main reason for the formation of nitrogen monoxide (NO). In order to reduce the temperature in the combustion chamber, it is possible to let the exhaust gas recirculate, by virtue of its relatively reduced temperature. This is obtained thank to the EGR valve, which leads the gas back to the intake manifold. The percentage of nitrogen oxides can be reduced significantly by increasing the portion of exhaust gas, but this may lead to a rise of the hydrocarbons and of the particulate matter. It must be noted that the EGR valve and its pipes are subjected to clogging, caused by the sediments. Therefore, it is not possible to consider the EGR valve as a reliable device in the long term and it is not anymore sufficient to comply with the limits imposed by the latest emission standards.

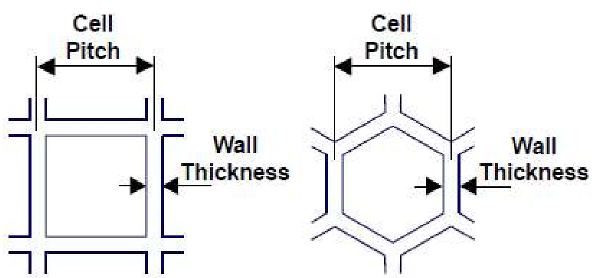
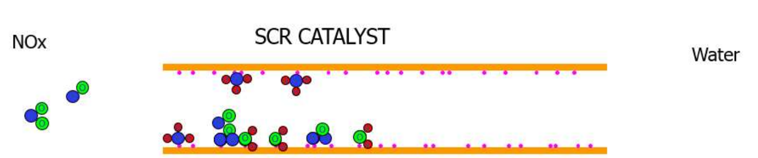


Figure 1-7: Different honeycomb structures.

Starting from Euro 6d, Selective Catalyst Reduction (SCR) is necessary on all Diesel vehicles. The adjective "selective" means that the reducing agent oxidizes with the oxygen contained in the nitrogen oxides and not with the molecular oxygen in the exhaust gas. In order to convert the nitrogen oxides into diatomic nitrogen (N_2) and water a reducing agent must be used, such ammonia or urea. Although the first one (NH_3) would be highly effective in the chemical reaction, it can be as well dangerous, because of its toxicity.

For this reason, urea, $(NH_2)_2CO$ is preferred. It is chemically stable, and it is highly soluble in water. "AdBlue" is the commercial name of the urea/water solution, while Denoxtronic is the name of the system which is responsible for the delivery and the dosing.

It goes without saying that the exhaust system becomes way more complicated with the presence of the SCR, because it will obviously require a urea tank, a pump and a dosing system. One of the most interesting aspects of the SCR is that it does not intervene in engine operations. In the Figure 1-8 it is possible to observe a scheme of the SCR reaction:



$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$$

Figure 1-8: A scheme of the SCR reaction.

Diesel Particulate Filter

The considered bracket is connected to the Diesel Particulate Filter (DPF). A more detailed description is therefore considered necessary.

Figure 1-9: A photo of a Diesel Particulate Filter.

The air around us contains numerous particles from various origins. The human body is not capable of shielding itself from particles smaller than ~10 µm, also known as PM-10.

The implications that these particles may have for the health have been studied in the last decades and a special attention was paid to the Diesel Particulate, which can be defined as the solid material originating from the exhaust gas. In fact, the carbonaceous portion of the particulate (called Diesel soot) comprises some compounds, which can be toxic and carcinogen.

One of the solutions to this issue is to filter those particles, therefore several technical solutions have been proposed. The general idea is to let the particles flow through a porous support, leading to the formation of a layer, called "filter cake". This layer has itself significant filtering properties and it continuously increases its thickness, augmenting the pressure drop. A certain time interval is therefore required in order to reach the steady state of the filter cake.

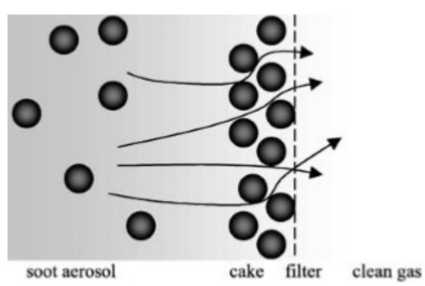


Figure 1-10: The filtering operations on the particulate matter. Reprinted from [1]

It must be pointed out that the quantity of particulate which is produced varies with the operating conditions and with the application. For this reason, the filter must be "tuned" to the actual requirements and it becomes really difficult to develop a single device that meets all necessities.

The DPF, as for the catalytic converter, can be made of ceramic or of sintered metal. The idea is to use channels, closed at each end by ceramic plugs. In this way the gas is forced to pass through the walls of the filter pockets, thus leaving behind the soot particles.

The efficiency which can be achieved in both situations can be higher than 95% for particle sizes between 10 nm and 10 μm [1].

When an excessive saturation occurs, the "regeneration" of the filter must be executed, because of the detrimental effect that it has on efficiency and acceleration power. The process should be carried out approximately every 500 km, even if this value may fluctuate significantly. During the regeneration, which takes from 10 to 15 minutes, the accumulated soot is basically burnt off.

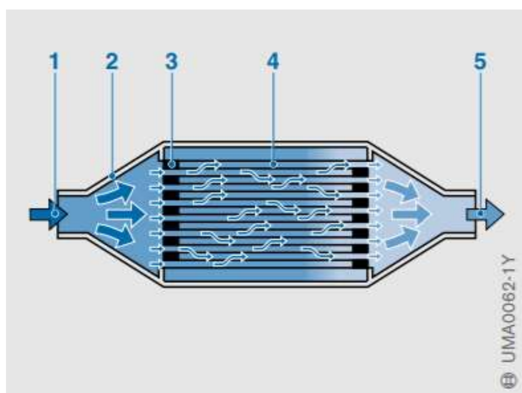


Figure 1-11: The functioning of the Diesel Particulate Filter.

Decreasing emissions by reducing the car weight

It is well known that the car weight and the fuel consumption are strictly linked. A weight reduction of 10% corresponds to a variation of the consumption between 3% and 7% [2].

Similar considerations also apply, *a fortiori*, to the aerospace sector, in which the cost of the fuel may amount to the 40% of the direct operating expenses. In this case the weight reduction is obtained by acting for example on the structure of seats or on the cargo containers, as well as with other expedients [3].

In order to diminish the car weight, two different strategies can be followed. The first and most self-evident one is reducing the size of the car, or "downsizing". In this case the weight of the redesigned car M' can be written as a function of the sum of the mass of each original material M_k, by using a scaling factor ε:

$$M' = (1 - \varepsilon) \sum_k M_k$$

In addition to being obvious, this strategy may not be satisfactory, because not necessarily the carmaker is willing to modify the size of the vehicle. Furthermore, some variations applied to the weight of a vehicle may be the reason why a vehicle is moved from a category to another, and so it may become subject to even more strict limitations on the emissions.

The second and most interesting alternative is to change the used materials. The possibility of substituting mild steel and cast iron with high strength steel, aluminum, magnesium or polymer composites has been widely investigated by Modaresi et al. (2014) [4].

The material may be chosen for several reasons, such as strength, stiffness, lower density, et cetera. The recyclability of the material should be taken into account, as well as the environmental benefits.

For example, composite materials may offer interesting mechanical properties and low density at the same time, but their production can be more energy consuming than other conventional materials [2]. This, combined with scarce possibilities of recycling, led to the abandon of this path, at least for the moment. Indeed, it must be certain that the environmental problem is not simply moved from the transportation sector towards others. For this reason, it is necessary to compute accurately the net savings in terms of emissions with the assistance of mathematical models, in order to make informed decisions.

Nevertheless, when it comes to modify the material of a mechanical part, it is indispensable to validate the design in the new situation, or more cleverly to redesign it from scratch. This thesis is part of this context: through Topology Optimization it is not only possible to obtain a lighter component, but also to achieve the best design.

Another side benefit is that having a lighter vehicle corresponds to a lower kinetic energy, and this is of course advantageous in case of a crash [5].

As always in the automotive industry, it takes a long time to observe a wide diffusion of new technologies in the market. In order to fully enjoy the benefits of lightweight vehicles, about two decades will be necessary, according to Serrenho et al. (2014) [2]. However, the consequences on the metal production industry may be overwhelming.

Chapter 2
A general introduction to Additive Manufacturing

Tons of papers have been already written regarding Additive Manufacturing. All of them share the same enthusiasm and the same expectations for this astonishing technology, which is revolutionizing the economy with its continuous advancements.

The idea behind Additive Manufacturing is at the same time elementary and powerful: building parts not by removing material, or by deforming it, or by casting, but simply adding it layer after layer. This happens without the use of tools and practically without any limitation in the complexity, on the basis of the digital model of the geometry.
Because of the finite and not infinitesimal thickness of the layers, the resulting part will be of course an approximation of the initial design. Obviously, if the layer is thinned, the final component will be closer to the CAD model.

Since the publication of the Stereolithography patent in 1984, several techniques have been developed. They employ different energy sources and use the material as solid, liquid or powder. Although, as for Stereolithography, the first patents dealt only with polymeric materials, some of them have been adapted for metals or ceramics. This was made possible thank to the enhancements in the software and in the hardware during the last decades (in terms of developments of laser sources and of improvements of processors).
This evolutionary process has gone hand in hand with the transition between "Rapid Prototyping" and "Additive Manufacturing". It must be remembered indeed that the parts obtained through Stereolithography were used initially as prototypes, therefore this one was the first application of this group of technologies. This implementation of 3D printing is perfectly still valid and effective, but in the last years it has been flanked by the possibility of building finished components. In this day and age, the second expression is universally preferred, as more representative of the current state of the art.

A short list of the steps which lead to the finished component is reported below. However, a more detailed description of each of them will be given in the next chapters of this thesis, when the building process of the redesigned bracket will be reported.

1- As it has already been mentioned, the CAD solid modelling is the indispensable starting point of the entire process;

2- The solid geometry is then transformed into a shell and the surfaces are discretized in triangles. The resulting file is in the STL format, or in similar formats;
3- The part is divided into slices. They can have constant thickness, or they can vary throughout the height of the part. Generally, the second option is precluded by technological constraints and it is not implemented in all technologies. The thus obtained file can be exported to the machine;
4- At this stage, the building process takes place. It must be preceded by the preparation of the machine. During the building itself, the machine is generally autonomous, thanks to the level of automation and to the sensors.
5- The supports, when they exist, must be detached from the printed part. This operation is executed manually when the supports cannot be removed in other ways (in some situations, such as in the Fused Deposition Modelling technology, they are water-soluble).
6- Some post-processing may be necessary. This includes additional cleaning of the part, heat treatments, polishing, et cetera.

It is possible to enumerate a long list of advantages of AM: among others, the aforementioned freedom in the geometry of the parts, which results in the possibility of realizing undercuts, cavities, overhanging features and so on. The possibility of obtaining a part through a single productive step and with a minimum intervention of the operator is another fundamental benefit. It is necessary to remember the great ease as well in the customization of the products: if a modification of an item is required, it can be obtained without any variation of the instrumentation. It shall be sufficient to adjust correspondingly the computerized drafting.

As always, the disadvantages are not negligible. They include the limitations in the dimensions of the parts, the low production speed and the restrictions in the numbers of materials that the machine can operate with.

Referring in particular to the quality of the product, the poor surface finish must be highlighted, as well as the high cost of materials and their small variety and finally, the necessity of adding the supports.

What appears clear is that Additive Manufacturing is not at the moment the right answer for all production needs. Since the cost of the production doesn't vary significantly with the complexity of the part, the AM becomes a smart choice when a certain threshold is exceeded, as it is shown in the well-known chart showed in Figure 2-1:

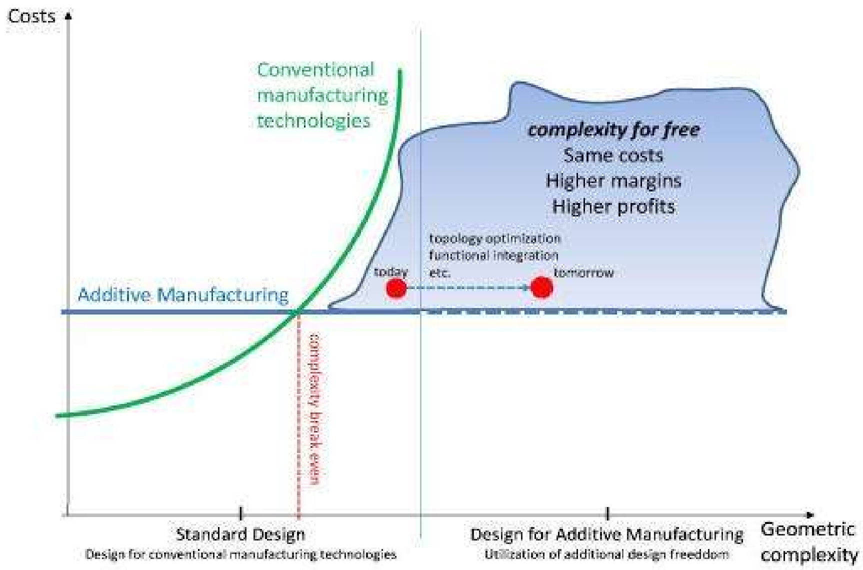


Figure 2-1: Economic justification of Additive Manufacturing. Source: Fraunhofer.

To support what is written above, the Standard ISO/ASTM DIS "Guidelines for design for additive manufacturing" [6] reports the following sentence: "If a part can be fabricated economically using a conventional manufacturing process and can meet requirements, then it is not likely to be a good candidate for AM".

Nonetheless, an economic justification can be found even for conventional parts. In fact, it may happen that a company is required to produce some parts with a high level of customization. Resorting to AM in cases like this may be an extremely intelligent alternative to tying-up a capital to acquire a way more rigid production system, such as molds.

Some comments can be made on the differences between AM and CNC machining, since they share the same computer-based approach to manufacturing. As a matter of fact, a CNC machine uses far less time to remove material than a AM machine to add a comparable volume. Moreover, while the parts obtained through AM may present voids and anisotropy, the CNC-machined parts are normally more homogeneous and of a predictable level of quality [7].

On the other hand, CNC machining requires more than one productive step, because of the indispensable changings in the positioning or even in the machine. In addition, some features cannot even be fabricated by shaving removal, unless they are divided into smaller parts, which will be then connected somehow. The clamps which are used during the machining process may represent a big limitation as well in the feasibility of the part, while the AM-obtained parts are not subjected to this kind of constraints.

An important turning point for public opinion was the expiration of the Fused Deposition Modeling (FDM) patent in 2009. This led to the diffusion of low cost 3D printers, which

nowadays are not uncommon in photocopy shops, next to inkjet printers. These machines mustn't be generally intended as industrial machines and their products are nothing more than toys or ornaments. The educational interest is nonetheless great, and rightly so.
On the contrary the high cost FDM machines can guarantee really small tolerances, which make them suitable even for really accurate applications, such as biomedical customized devices. The difference in price can be of one entire order of magnitude.
Using 3D printing in everyday life has become such a common thing, that in the software package which comes with Windows 10, two dedicated programs have been included. The well-aged "Paint" has been flanked by "Paint 3D", while "Microsoft 3D Builder" is a brand-new software, which is able of performing a wide range of operations on STL files.

Figure 2-2: The logo of a free Microsoft software for Additive Manufacturing

This is exactly what it was predicted more than ten years ago by Hopkinson, Hague and Dickens in their famous book "Rapid Manufacturing: An Industrial Revolution for the Digital Age".
In the context of mechanical engineering, particular relevance has been obtained by the development of the technologies for metals, because of the attractive prospects in the automotive or in the aerospace fields.

Additive Manufacturing for metals

It is possible to consider two families of techniques for printing metal parts and both of them use the material as powder. The first one is a "powder bed" process, while the second one is a "direct" technique.
As energy sources, it is possible to adopt a laser or an electron beam. What characterizes both cases is the possibility of concentrating the energy in a really little spot, and so attaining a high energy density. This idea originates without any doubt from laser welding, for which this results in a reduced Heat Affected Zone (HAZ).
Speaking of Additive Manufacturing, a small melt pool, and therefore a little melt volume means high solidification rates, with interesting implications in the microstructure.
Additive Manufacturing for metals can be implemented also in different fields than automotive or aerospace industries, for example in biomedical applications. Countless examples of

customized devices are currently printed, by making use of the advantages of Additive Manufacturing, along with an intense study on the biocompatible materials, such as Titanium Alloys. This application of AM was already started a long time ago with the utilization of polymeric materials, and it led to the early examples of end-usable products, widening the area of application of 3D printing, then just limited to prototyping. As a matter of fact, the opportunities offered by metals are broader than those permitted by polymers, also because of the higher stresses which this class of materials can tolerate (unless some engineering plastics, such as PEEK are considered).

Figure 2-3: A human printed mandible. The porous internal structure is designed to promote the bone ingrowth.

Substantial progress has been made in dental implantology and in endoprostheses (artificial devices which are placed inside the body and not externally, like the esoprostheses).

Another extremely interesting area of application is the conformal cooling for Injection molding (this branch of AM is often referred to as “Rapid Tooling”).

It is a well-known fact that cooling plays a key-role in this manufacturing technology for several reasons, primarily because the cooling time employs a large part of the cycle time (from 50% to 80% [8]). In other words, the part cannot be pulled-out of the mold, unless a certain equilibrium condition is reached. Secondly, a more uniform temperature distribution guarantees a better level of quality, in terms of warpage and sink marks.

In the conventional cooling the plates are generally drilled, hence the channels must be straight, albeit not necessarily arranged on a single plane. This of course limits the possibility of adapting the channels to the shape of the part.

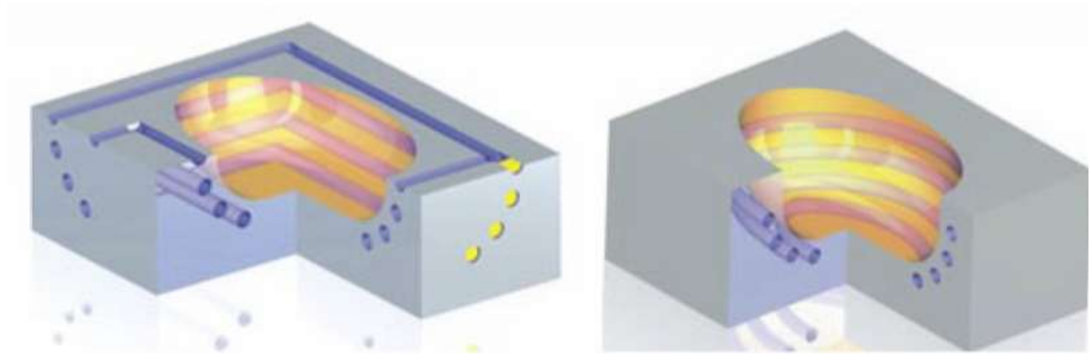


Figure 2-4: A mold with conventional cooling (left) and with conformal cooling (right). Reprinted from [8]

With conformal cooling instead, the channels can actually “wrap” the part, improving the thermal exchange. The cross section can take almost any shape, in order to reach a desired Reynolds number and so achieving the desired turbulence of the coolant.

The theoretical concept of conformal cooling can be put once more into practice by means of AM. The production and the design of the mold inserts has significant repercussions on the upfront investment costs, but it has been extensively demonstrated that the number of parts produced per unit time grows considerably and that the scrap rates are reduced. According to reports, the cycle time savings range from 15% to 45% [9].

As it is possible to observe in the Figure 2-5, the breakeven point is reached before for a mold with conformal cooling, despite the fact that the vertical intercept is undoubtedly higher in this case.

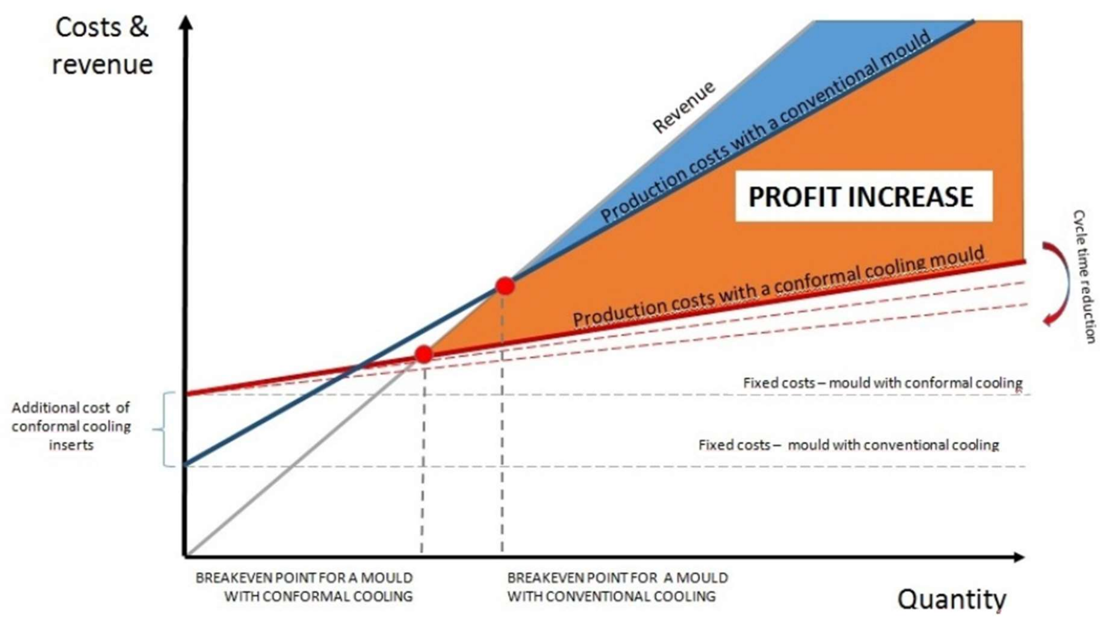


Figure 2-5: Economical justification of conformal cooling for Injection molding. Source: Fado.

Similar remarks may be made for cooling in Die Casting or for heating purposes.
However, when it comes to large parts, the limitations in the sizes of the process chambers of the machines become a big restriction to the growth of this technology.
A more important restriction to the development of research in AM for metals is represented by the high cost of the raw material, especially when it comes to print large-scale parts. The density which characterizes some alloys, coupled with the price per kilo, leads to huge costs. This cannot be but a hindrance to a wider and faster diffusion of this branch of 3D printing.

Selective Laser Melting

Like all the other Additive Manufacturing techniques, Selective Laser Melting (SLM) allows to build mechanical parts, simply using a 3D model and an energy source.
As for Selective Laser Sintering (SLS), SLM is a powder bed technique. This means that a thin layer of metallic powder is distributed over the building plate, with a recoater. Then, some predefined regions of powder are melted, using a focused laser. At this point, the platform is lowered correspondingly to the height of a layer, and the process is repeated until the part is complete.

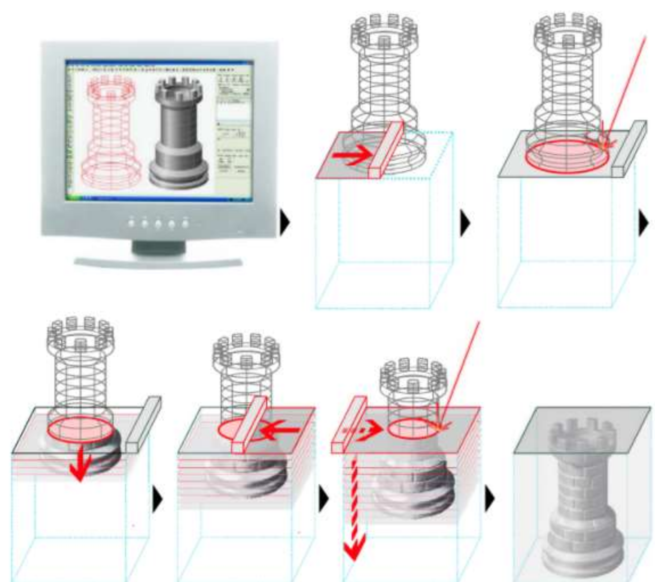


Figure 2-6: An overview of the various steps of SLM. Reprinted from [10]

A protective gas is fed into the chamber, in order to minimize the presence of oxygen and therefore to prevent the oxidation of the metallic powder. At the same time, the continuous gas flow helps the removal of the by-products of the process (essentially smoke precipitates), heading them towards the recirculating filter. A small portion of these metallic droplets remains anyway into the powder bed and must be isolated with the sieve from the re-usable powder [10]. In the past years, the various producers patented different solutions to manage the inert gas flow.

The main difference between SLS and SLM is that, although these two techniques share the same processing apparatus, the latter is based on a complete melting of the powder. This has been enabled thank to the continuous improvements in the lasers technology, and in detail in the power and in the dimensions of the focused spot. Therefore SLM machines resort to high density laser sources, such as CO_2, Nd:YAG or fiber lasers. Mechanical parts obtained through SLM show superior mechanical properties, reaching almost 100% density [11].

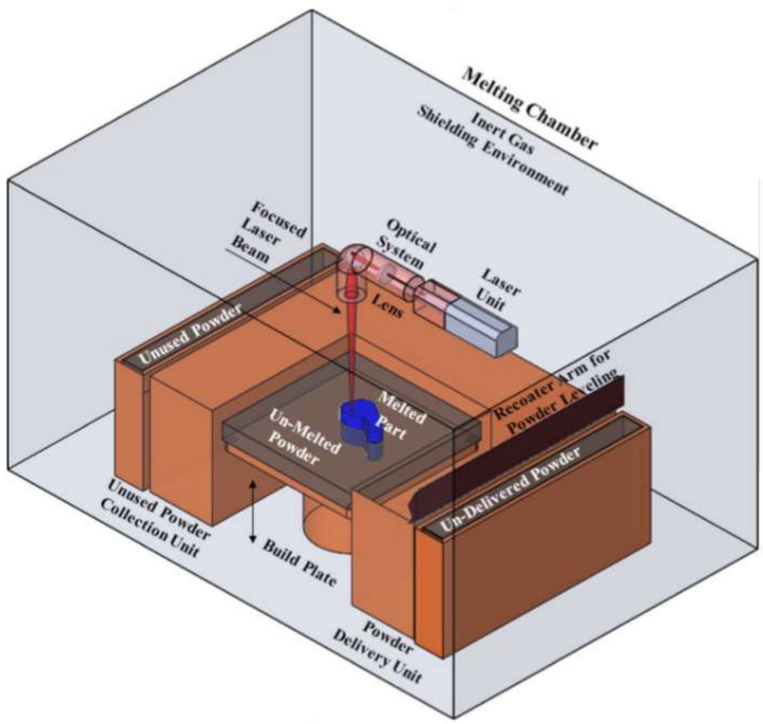


Figure 2-7: A scheme of a SLM machine. Reprinted from [12]

In the final analysis, SLS is applied to a variety of materials (ceramics, plastics…), while SLM is currently referred as the technology which deals with metals.

Several process parameters can be imposed: laser power, scanning speed, hatch spacing, layer thickness, et cetera. The machine producers provide some suggested values for the most common and tested materials. It is important to point out that any variation, even for laboratory testing, should be carefully assessed, because of the large oscillation of the results in terms of quality. Due to the large number of variables and to the scarce repeatability, it is not easy to define the optimized parameters for all applications.

A large and still growing number of different metallic powders is currently used for SLM. Generally, pure metals are not applied to AM processes, because of the well-known poor mechanical properties and the high tendency to oxidation and to corrosion. Despite some attempts (with pure Titanium or Copper), the usage of pre-alloyed powders is preferred.

In their respective price lists, EOS and Renishaw propose one Aluminum alloy, various stainless steel and austenitic nickel-chromium-based super alloys (Inconel), Cobalt-Chrome alloys, Titanium alloys and Maraging Steel.

Good examples of materials still under observation, but not yet among the standardized ones, are tool steel H13 and M2 high speed steel, because of their brittle nature and the consequent high percentage of cracking[2].

When a new material needs to be marketed, a long procedure needs to be followed, with the aim of finding the appropriate process parameters.

As an example, the search for the optimum parameters to print Invar 36 is a common topic in the recent scientific literature. This Iron-nickel alloy is well known for its extremely low thermal expansion coefficient and it is used in the aerospace industry. One of the parameters to be detected is the laser power: if the value is too low, the final part will be affected by an unacceptable low density, while if it is too high, the material may even be vaporized. A high power will lead to a better final density of the part, but the nickel content will be somehow reduced. This is an extremely undesired effect, because the variation of the percentage of the nickel would affect the favorable thermal expansion coefficient, which is actually the main reason to use InvarFigure 2-7: A scheme of a SLM machine. Reprinted from

The Invar example is maybe representative of the difficulties which may be faced in the research for the optimum process parameters for a new material. The contribution made in this field by Universities throughout the world is fundamental for the advancement of technology.

Indeed, it must be pointed out that in addition to the machine producers, numerous powder suppliers are entering the market in this moment in time. This is unequivocally disturbing the balances and it allows more easily to obtain custom-made powder mixtures.

Many recent papers are presenting also the possibility of obtaining composites, mixing precise amounts of different powders (Metal Matrix Composites).

[2] To reduce the high residual stresses, the possibility of preheating the build plate has been investigated recently. For further details, please refer to "Influence of Powder Bed Preheating on Microstructure and Mechanical Properties of H13 Tool Steel SLM Parts" by Mertens et al. (2016), or to "Producing crack-free, high density M2 HSS parts by Selective Laser Melting: pre-heating the baseplate" by Kempen et al. (2013).

A bigger attention will be paid to Selective Laser Melting in a following paragraph, because it has been used for the construction of the bracket.

Direct Metal Deposition

As for SLM, this technique employs a laser as an energy source. The main difference is that the metallic powder is not deposited on the building plate in advance, but it comes out of a nozzle, as well as the laser beam. The nozzle is then directed to the exact position of interest, moment by moment.

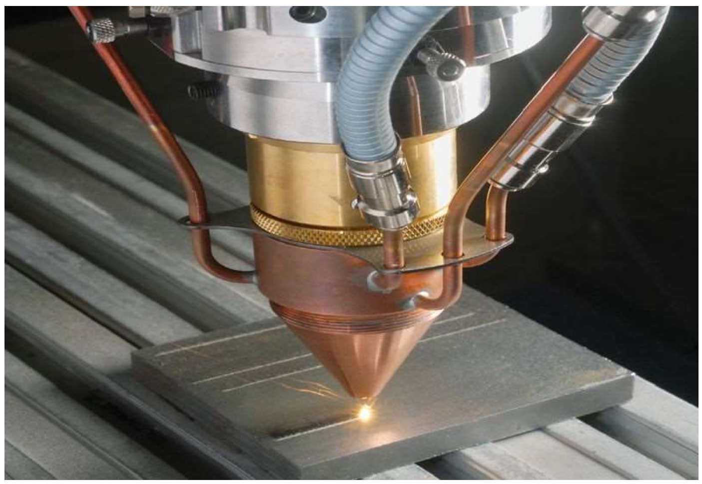


Figure 2-8: A nozzle operating on a building plate during a DMD process. Source: Fraunhofer.

The nozzle plays obviously a fundamental role in the process and it can take two different configurations: coaxial or multijet. In the first case, the powder flows out of the circular ring which surrounds the opening for the laser beam, while in the second one the powder originates from a various number of ducts, arranged circumferentially around the laser beam. In both situations it is necessary to use a shaping gas, which helps the powder to flow and a shielding gas, which prevents the melt pool to oxidize.

The multijet configuration is actually the evolution of the lateral single-nozzle arrangement, which is more similar to the traditional welding techniques. In this case the laser and the powder flow are not coaxial. Even if this configuration is now less common, it is available commercially and still used by several research groups. In the following figure the different kinds of nozzles are recapitulated.

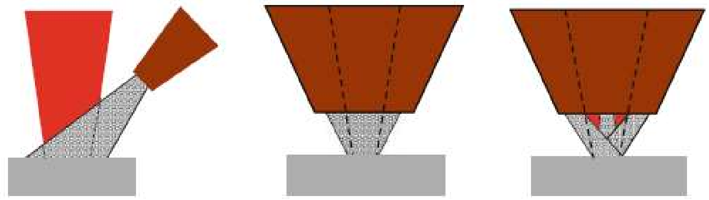


Figure 2-9: The three main nozzle structures for DMD. Lateral, coaxial and multijet.

Several considerations can be made on the best conicity angle of the nozzle for the flowability of the powder and above all for the reflection of the laser radiation. Since the processed material is a metal, a certain percentage of the laser wave is in fact reflected toward the nozzle, causing a temperature rise, especially on the bottom of the nozzle, causing damages of the device. This heat may induce a partial sintering of the powder, before it leaves the nozzle, leading eventually to the clogging of the openings. This problem is handled by choosing a material with high reflectance (for instance, copper alloys), and by designing some cooling channels, possibly conformal [12].

Direct Metal Deposition is sometimes referred also as Laser Cladding. As the name suggests, since the material is directly positioned on the part, it is actually possible to repair some mechanical component subjected to heavy wear, with results far more interesting than with other techniques, such as TIG welding [13].

It is possible in fact to compare the damaged part with the original CAD model, using some Reverse Engineering systems. At this point the quantity of material and the exact portion from which it was removed will be computed accurately, then the nozzle will deposit the necessary material on the affected spot.

This application of DMD has been widely studied in the past years and it is still studied, because it may have an extremely interesting application in the refurbishment of turbine blades [14].

Electron Beam Melting

Unlike the two previously described technologies, Electron Beam Melting (EBM) uses an electron beam as an energy source.

Once the electrons are generated in a gun, they are accelerated thank to a potential difference, then they are focused using electromagnetic lenses. At this stage, they are electromagnetically scanned on the basis of the CAD model. Before than the real scanning, the powder bed is preheated with multiple passes at high current, reaching more or less $0.8T_m$ (the melting temperature). For the final scan the current and the scanning speed are both reduced.

When the electrons (streaming at about half the speed of light) impact with the metal powder, their kinetic energy is instantly converted into thermal energy, and the temperature is raised above the melting point.

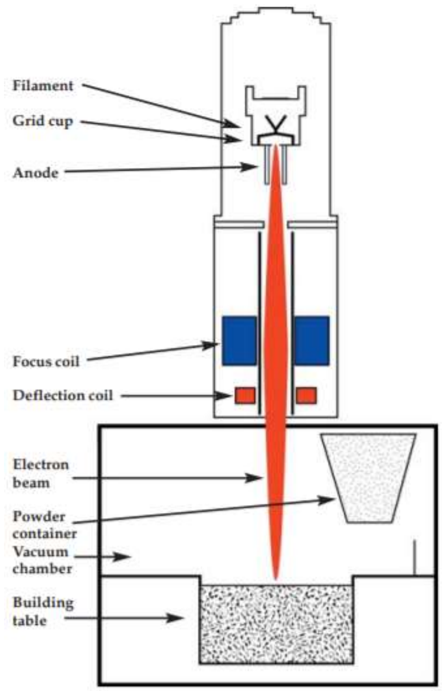


Figure 2-10: A scheme of the EBM technology. Source: Arcam.

Since the electron beam is directed by changing the electromagnetic field, there is no need for scanning mirrors, nor to move any mechanical part (the gun is stationary). This may reduce significantly the time required for the scanning.

As always happens for Electron Beam systems, the procedure should be executed in high vacuum conditions, in order to avoid the slowdown of the electrons because of the collision with air or gas molecules.

This process is declared to be 95% energy-efficient and then from five to ten times more effective than the laser technologies for metals [15].

Focusing on Selective Laser Melting

SLM is the technique which has been used to build the part. A more detailed study of this process appears therefore appropriate.

Hot Isostatic Pressing (HIP)

It must be pointed out that most of the observations made in this short paragraph apply not only to SLM, but to all powder-based additive manufacturing technologies for metals.
HIP is a well-established method to enhance the mechanical properties of a part, by reducing the internal porosity, for instance after a casting process.
HIP is the application of high temperatures and high pressures to a mechanical part, by using an inert gas, such as Argon. Because of the high temperature, the yield strength reduces, while the diffusion rate increases. As a result, the pores contained in the component collapse, thank to small scale plastic flows and ideally the pore interfaces are bonded.
Although printed mechanical parts show mechanical properties which are comparable to those of a traditionally wrought part, a certain scatter has been observed in high-cycle fatigue life. This is mainly due to pores, which act like crack initiation sites. The removal of these crack sites has been shown to be extremely efficient in extending the fatigue life, also because of the microstructural coarsening which occurs in high-temperature HIP cycles. The possibility of applying HIP also for AM parts has been investigated in several researches.
Tammas-Williams et al. (2016) [16] pointed out that after a HIP treatment applied to Ti-6Al-4V samples at 1193 K and 100 MPa for 2 hours, all residual voids collapsed under the resolution limit of the equipment (~5 μm).
On the contrary, on the same research it was surprisingly discovered that HIP can even exacerbate things when it comes to surface-connected pores, which unfortunately can become extremely effective crack initiation sites. In traditional manufactured components a coating is applied prior to HIP, in order to avoid this issue.

It must be remembered that HIP can be used as well as a manufacturing technique *tout court*, for instance for the fabrication of materials which are difficult to be machined (powder metallurgy). This idea has been used in a 2017 research [17], which combines HIP with SLM, considering it as a manufacturing process and not just as a post-processing method. The initial idea of the research is that more than 80% of the total processing time of SLM is occupied by the scanning, when building large volume parts. The interesting idea is to scan only the

external shell of the part with the laser. The internal unmelted powder will be then consolidated through HIP, thus reducing the processing time.
This is not much different than the Stereolithography (SLA) idea, after all: the skin of the photopolymer is scanned by a laser beam, then the entire body is moved to an ultraviolet oven to completely solidify the part.
In particular, good bonding resulted between the shell and the HIPed portion. However, the microstructures were undoubtedly different for the two regions: with coarse columnar grains for the shell and with finer equiaxed grains for the inside.

Heat treatment

As a matter of fact, the mechanical behavior of 3D printed mechanical parts can be very dissimilar from conventionally manufactured parts, as a consequence of the profound differences in the microstructure.
Generally, the heat treatment for SLM parts is performed without any variation of the microstructure. Nevertheless, it is the simplest solution to alleviate residual stresses, which are practically unavoidable in AM for metals, as a result of the high cooling rates. Nevertheless, the heat treatments for metallic parts obtained with SLM are not yet standardized.
In addition to the expected reduction of the strain, the heat-treated specimens present many other advantages. It has been observed in fact that the breaking elongation may be significantly enhanced after heat treatment [18], as it is possible to notice in the Figure 2-11.

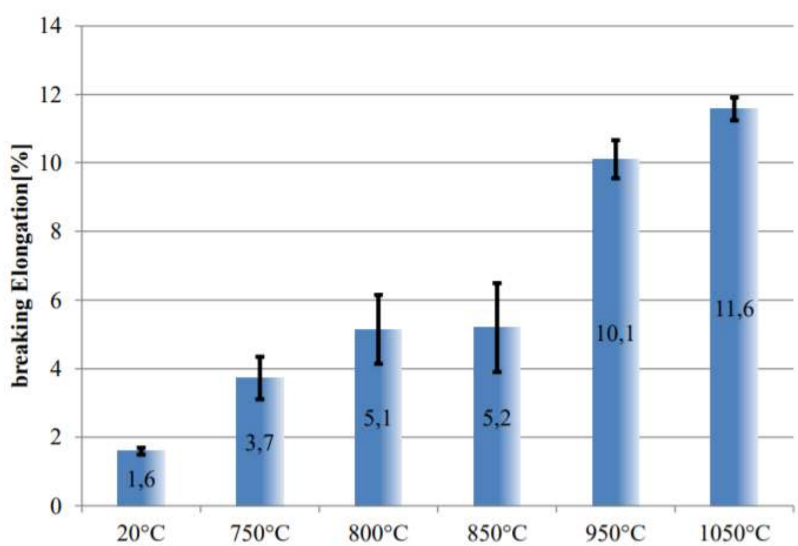


Figure 2-11: Breaking elongation of heat-treated Ti6Al4V samples at different values of temperature. Reprinted from [19]

The effects of the heat treatment on the mechanical behavior of printed parts can now be predicted by simulation programs, such as Netfabb.

Some technicians suggest heating the process chamber once the machine has been loaded with the powder, some hours before the printing process starts. This should help in reducing the humidity contained in the powder and thus it should lead to a better quality of the part. Nevertheless, no scientific validation can be found in the literature for this statement.

Machining after printing

Machining of 3D-printed metal parts is receiving an increasing attention. Because of the not always satisfying surface roughness, some grinding and some polishing are often necessary. In other cases, for instance, the high-precise threading of the holes of a part is not included in the STL model, but it is carried out after the building process. Some machining is fundamental also when destructive tests must be executed on printed metal samples, which will include a machining allowance.

Finding the best process parameters to machine “tricky” materials obtained through traditional manufacturing technologies is already difficult. When it comes to 3D-printed metal, the situation becomes even more complicated, not only because the obtained microstructures are different from those which can be found in traditionally manufactured parts, but also because the building direction may play a fundamental role. It must be remembered in fact that the powder producers suggest different values of the Yield strength, depending on the chosen direction for the printing.

In a recent paper by Fortunato et al. (2018) [19], the milling process of Maraging steel printed parts has been investigated. The building direction was included indeed among the considered variables of the research.

The heat-treatment is an important variable to consider as well, because it generally causes a residual stress relieving and a more homogeneous microstructure. When it comes to Maraging steel, the annealing treatment may be followed by the ageing treatment, which is necessary to obtain some desirable intermetallic precipitates. The two treatments have completely different durations and should not be confused. Fortunato suggests performing the solutioning for one hour at 815 ˚C and the ageing process at 480 ˚C for four hours.

In the same paper the advantages of performing the heat-treatment before than the machining were underlined.

Generally, if the cutting speed is raised, this results in a reduction of the cutting forces, because of the localized thermal softening. Although in the solutioned and aged samples the cutting forces decreased, in the as-built parts they even showed the opposite trend, because of a higher tool wear.

Multi-beam strategies

Another important tactic to increase the productivity can be the usage of more than one laser beam at the same time.

During 2013 the SLM 500^{HL} model of SLM Solutions was presented and it included 4 lasers and 4 scanners, but since then similar systems have been extended to many other machines. This allows to build several small parts simultaneously, or even to fabricate a single big part. Of course, attention must be paid to the integrity of the part in the borders between the different areas, managed by different lasers. For this purpose, a certain overlap should be defined [20].

Using more than one laser beam may also be an interesting approach as well to reduce residual stresses. Indeed, it has already been proved that pre-heating or post-heating the layers with the melting laser has a positive effect. Heeling et al. (2016) [21] suggest using a second laser beam to execute exclusively these heating strategies.

Multi-material processing

The possibility of printing with more than one material at the same time, which is already a well-established possibility of other AM technologies[3], has been investigated in some recent researches also for SLM. This wonderful opportunity could be applied in an extremely wide range of fields, such as electronics or medical implants.

A recent paper introduced an interesting system to perform this kind of process for SLM [22]. The idea is to use powders of different materials, having different sizes. The layers of the various materials are sequentially applicated on the building plate and then scanned. The unsintered powder is removed before than the new material is deposited, then the procedure is repeated for each material of the same layer. The different materials are then filtered because of their differences in the particle size. In order to deposit various materials on the same layer, once the first material is sintered and the un-sintered powder is removed, the building plate must be raised of the same height of the last layer. Because of this continuous movement of the building plate, this is indeed referred as "building piston".

The different powders should be stored in as many feeding containers. The recoater used in the standard SLM technology should be substituted by an array of hopper-nozzles.

[3]For further details, please refer to "Multiple material additive manufacturing – Part 1: a review" by Vaezi et al. in "Virtual and Physical Prototyping" (2013).

An important issue of this method is the cleaning of the previous powder before than the deposition of the new one. This cannot be achieved only mechanically, but with a combination of a mechanical device and of a vacuum cleaner.
It is not clear how it would be possible to remove the powder of the last layer with a vacuum cleaner, without removing also the powder which has a support function. Moreover, there is no mention of practical aspects, such as the overlap which should be considered between the various material regions on the same layer.
This method is not yet commercially available, and it seems undoubtedly way more complicated than the multi-material direct process, which uses different nozzles at the same time, instead of a powder bed.

Lattice structures

Recently, metallic lattice structures drew attention, because of their incredible aptitude in absorbing shock energy. This makes them extremely suitable for biomedical prostheses of human bones, but also for heat exchangers (replacing the fins).
Lattice structures, which can be obtained with AM, share this ability with metal foams or honeycombs, currently obtained by conventional manufacturing technologies. The main difference is that metal foams have a random distribution of pores, whereas lattice structures are tridimensional organized truss cells. For this reason, simply varying the geometrical characteristics (such as the shape of the cells, or the dimensions of the trusses), it is possible to control the stiffness of the structure at every position [23].

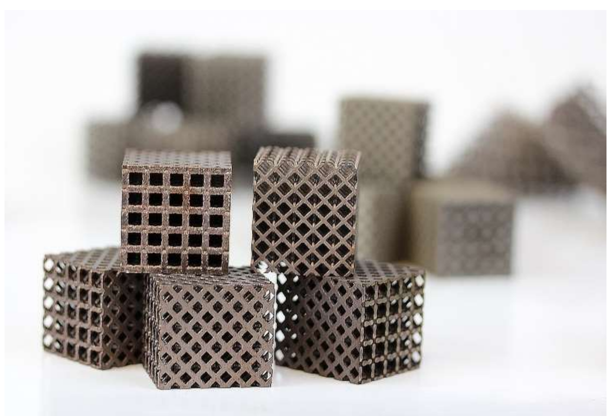


Figure 2-12: A photo of different lattice structures. Source: Northwest Aerospace Alliance.

Countless unit cells are currently studied and printed, and new ones are continuously proposed, having sometimes quite exotic names: star, spider, dark horse, snow flake, and so on.

They can be classified on the basis of the volume fraction, or the ratio d/a (diameter of the trusses/length of the unit cell).
Several programs, such as Netfabb or nTopology help the users in creating the lattice structures which better fit the considered volume, giving also the possibility of trimming the protruding portions, or having trusses with variable cross sections.

Choosing the material for the redesigned part

The bracket is originally made of Cast Iron GH 45-33-15 (according to the Fiat standard no. 52215) and it weighs 2.1 kg. The same material is referred to as GS 450/10, according to UNI ISO 1083. In the Table 2-1 it is possible to read some of the most important properties of this material. More detailed information could not be found.

Table 2-1: Some mechanical properties of Cast Iron GH 45-33-15

R_m	440 N/mm^2
$R_{p0,2}$	310 N/mm^2
Elongation A%	13%
Brinell hardness	150 ÷200

The importance of choosing the right material for the purpose of pursuing a weight reduction of vehicles has been already discussed in the first chapter of this thesis.
As already mentioned, the possibility of using composite materials to achieve weight reduction has been considered and then discarded by companies, due to the high amount of energy and of emissions which is linked to their production. However, when it comes to Additive Manufacturing for metals, the composite materials are basically obtained by mixing powders of different materials (MMC). Therefore, it is not possible to observe a significant variation of the costs of the material, compared to those of the standardized powder, because of the not much more complicated preparation process. The same holds true with regards to the pollution associated with their production.
Because of the fact that this is a brand-new research topic, the idea of using MMC has been discarded. Nevertheless, it may be an interesting alternative for future projects related with topology optimization for Additive Manufacturing.

Why not Cast Iron?

Cast iron is not among the available materials of the most important producers of powder for SLM. The main explanation for this is the same reason of the scarce weldability of this material, i.e. the high content of carbon (> 2.1%).
First of all, it must be pointed out that generally welding on cast iron involves repair operations on castings, and not joining castings to other elements. In fact, damages on cast iron parts are not infrequent, due to the fragile behavior of this material.
The weldability of Cast iron depends on several factors, such as the chemical composition, the type of filler material and preheat/post heat treatments.
In practice, the high carbon percentage leads to the formation of hard brittle phases in the fusion zone and in the heat affected zones, namely martensite and carbides. This cannot be but detrimental to the ductility, the toughness and the machineability of the part.
It must not be forgotten that even the type of cast iron plays a fundamental role. For instance, in grey cast iron the low ductility is already due to the graphite flakes. On the contrary, the nodular graphite in ductile cast iron makes the material more suitable for welding. Lastly, white cast iron is considered unweldable, because of the presence of iron carbides [24].

Even if the most common processes for cast iron are arc welding and oxyacetylene welding, friction welding and electron beam welding are now currently studied [25].
Nevertheless, some advances have been made recently. A 2017 paper investigated the possibility of using SLM to join 304L stainless steel on a cast iron substrate [26]. Using a pulsed laser, it is in fact possible to reduce the overall energy input, obtaining smaller welded pools and at the same time, enhancing the weldability.

Because of the research is still at an early stage and because it was planned to modify the material in any way, the possibility of using Cast iron powder has been discarded from the beginning.

Maraging steel

This genre of steels achieves its ultra-high strength through the precipitation of intermetallic compounds, typically with nickel, cobalt and molybdenum. Carbon is considered an impurity element and it is kept at a really low percentage. This results in a successful combination of toughness and strength.

The name “Maraging” refers to the ageing of martensite. This microstructure is easily obtained because of the high nickel content. This element appears in fact along with molybdenum in the equivalent carbon content formulas, used to determine weldability.
Since carbon free martensite is quite soft, a heat treatment (ageing) is often operated for several hours between 480 and 510° C. During this process, the precipitation hardenings occurs before than the austenite phase can appear.
In the Table 2-2 it is possible to analyze an example of the chemical composition of different kinds of Maraging steel, accompanied with the corresponding Yield strength values.

Table 2-2: Various types of Maraging Steel.

Alloy designation	Ni	Mo	Co	Ti	Al	Y_S (MPa)
18Ni (200)	18	3.3	8.5	0.2	0.1	1400
18Ni (250)	18	5.0	8.5	0.4	0.1	1700
18Ni (300)	18	5.0	9.0	0.7	0.1	2000
18Ni (350)	18	4.2	12.5	1.6	0.1	2400
18Ni (cast)	17	4.6	10.0	0.3	0.1	1650

The self-evident downside of all these wonderful features is the high cost of the alloying elements, and especially of cobalt. This problem has influenced for long time the direction of research and the goal is still to obtain a cobalt-free low cost Maraging steel with the same properties of the current one [27].

The Maraging steel available for the printing process is the 18% Ni Maraging 300, or with the German notation X3NiCoMoTi 18-9-5. The used powder for the printing of the brackets has been purchased from the German company EOS, and it is sold with the name MS1 Maraging Steel. According to EOS brochure, it is possible to apply spark erosion, welding, micro short-peening, polishing and coating.
The density varies between 8.0 and 8.1 g/cm^3, while expected relative density is approximately 100%.
In Table 2-3 some technical data at 20°C are showed, as declared by the producer. The values vary, depending on whether the ageing treatment is executed or not, but they also vary with the building direction.
Those data have been used to validate the results originating from Topology optimization.
As it is possible to observe, the declared mechanical properties of the as-built Maraging Steel are excellent, even where the ageing treatment is not performed.

Maraging Steel finds widespread applications in automotive and aerospace industries, dies with conformal cooling and shafts.

Table 2-3: Mechanical properties of Maraging Steel, according to the EOS data sheet.

	As built	After age hardening [2]
Tensile strength [6]		min. 1930 MPa min. 280 ksi
- in horizontal direction (XY)	typ. 1100 ± 100 MPa typ. 160 ± 15 ksi	typ. 2050 ± 100 MPa typ. 297 ± 15 ksi
- in vertical direction (Z)	typ. 1100 ± 100 MPa typ. 160 ± 15 ksi	
Yield strength (Rp 0.2 %) [6]		min. 1862 MPa min. 270 ksi
- in horizontal direction (XY)	typ. 1050 ± 100 MPa typ. 152 ± 15 ksi	typ. 1990 ± 100 MPa typ. 289 ± 15 ksi
- in vertical direction (Z)	typ. 1000 ± 100 MPa typ. 145 ± 15 ksi	
Elongation at break [6]		min. 2 %
- in horizontal direction (XY)	typ. (10 ± 4) %	typ. (4 ± 2) %
- in vertical direction (Z)	typ. (10 ± 4) %	
Modulus of elasticity [6]		
- in horizontal direction (XY)	typ. 160 ± 25 GPa typ. 23 ± 4 Msi	typ. 180 ± 20 GPa typ. 26 ± 3 Msi
- in vertical direction (Z)	typ. 150 ± 20 GPa typ. 22 ± 3 Msi	
Hardness [7]	typ. 33 - 37 HRC	typ. 50 - 56 HRC
Ductility (Notched Charpy impact test)	typ. 45 ± 10 J	typ. 11 ± 4 J
Thermal conductivity	typ. 15 ± 0.8 W/m°C typ. 104 ± 6 Btu in/(h ft² °F)	typ. 20 ± 1 W/m°C typ. 139 ± 7 Btu in/(h ft² °F)
Specific heat capacity	typ. 450 ± 20 J/kg°C typ. 0.108 ± 0.005 Btu/(lb °F)	typ. 450 ± 20 J/kg°C typ. 0.108 ± 0.005 Btu/(lb °F)
Maximum operating temperature		approx. 400 °C approx. 750 °F

Chapter 3
Topology Optimization

The main goal of Topology Optimization is to arrange the material within a design domain, with the aim of obtaining the best structural performances. Even if it was first applied to mechanical problems, it has been thereafter used in other fields, such as Fluid Dynamics, Acoustics, Electromagnetism, Optics or different combinations of them [28].

For several years one of the most important limitations has been represented by the technologic constraints. These restrictions can be completely overcome resorting to Additive Manufacturing.

Unfortunately, this does not mean that the results coming from the optimizer don't need any post-processing or that they are always easy to be interpreted. It is necessary indeed a translation process, which will lead eventually to a reasonable and intelligent design.

Mathematical formulation of the problem

The Topology optimization problem can be written as follows:

$$\begin{cases} min_{\rho}: \quad F = F(\boldsymbol{u}(\rho), \rho) = \int_{\Omega} f(\boldsymbol{u}(\rho), \rho) dV \\ s.t.: \qquad G_0(\rho) = \int_{\Omega} \rho(\boldsymbol{x}) dV - V_0 \leq 0 \\ \qquad\qquad G_i(\boldsymbol{u}(\rho), \rho) \leq 0, j = 1, \dots, M \\ \qquad\qquad \rho(\boldsymbol{x}) = 0 \; or \; 1, \forall \, \boldsymbol{x} \in \Omega \end{cases}$$

Where u is a field who satisfies a state equation.

The goal is to find the best distribution of the mass which minimizes the objective function F. G_0 is a volume constraint and it prevents the volume from increasing during the computations. There exist problems for which this constraint is not necessary. Nevertheless, even for these problems, this condition may improve general convergence, or it may be used as a starting point for the successive iterations. The numerous G_i represent the various design criteria which have been taken into account.

Various algorithms have been developed to solve the structural optimization problem.

Evolutionary based algorithms

Once the design domain has been discretized, a certain value is attached to each finite element: 1 when the element is filled with material or 0 in the reverse case. As a consequence, the filled elements are represented as black and the empty ones are white (in a 2-D plot).

This method is extremely computationally expensive, because it is "population based". This means that the elements of the population must be of the same order of magnitude as the optimization parameters. Solving this problem through this evolutionary algorithm becomes practically impossible when it comes to tridimensional cases.

A strategy to reach a solution to the problem is to progress gradually, refining the mesh at every step.

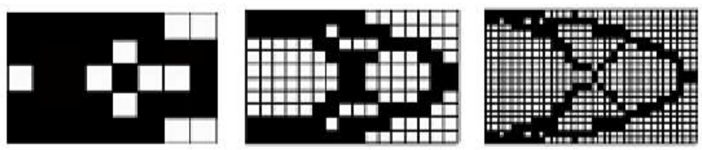


Figure 3-1: The consecutive mesh refinement in a Topology Optimization problem. Reprinted from [30].

It can be frequent to incur connectivity problems, because of the discrete representation of the domain. This is closely related to the so-called "checkerboard problem", which occurs in "hard-kill" methods such as this one, when adjacent elements are alternatively white and black.

The connectivity problem can be overcome in various ways, such as dynamically penalizing disconnected elements [29].

Solid Isotropic Microstructure with Penalization (SIMP)

SIMP is undoubtedly the most studied method and the most used for commercial programs.

Unlike the previous one, this is a "soft-kill" method: this means that the domain is still discretized, but in this case only a fractional material density ρ_e is assigned to each element (grey elements).

The objective is to minimize the strain energy SE, whilst having a specified target volume V*.

The optimization problem can be written as follows:

$$SE(P) = \sum_{e=1}^{N} (\rho_e)^p [u_e]^T [k_e][u_e]$$

$$V^* - \sum_{e=1}^{N} V_e \rho_e = 0$$

$$0 < \rho_{min} \leq \rho_e \leq 1$$

In the previous equations, u_e represents the nodal displacement vector, while k_e is the rigidity matrix of the element. The exponent p is a penalty factor and it is necessary to favor either black (ρ=1) or white elements ($\rho=\rho_{min}$).

Defining carefully the value of p is the key to the success of the method. The suggested value should be between 2 and 4 and its most common value is 3 [30]. However, to facilitate convergence p should be set at first to 1 and then increased during the subsequent iterations.

During the first iteration the initial density of the structure is taken into account. This passage is necessary to compute the sensitivity of each element, in other words the influence that the variation of density has on the objective function. Obviously, when the sensitivity is high, that means that the element must be maintained and added to the structure. The sensitivity can be computed as follows:

$$\frac{\partial SE}{\partial \rho_e} = -p(\rho_e)^{p-1}[u_e]^T[k_e][u_e]$$

The checkerboard problem can occur also using the SIMP method, if the sensitivity of different elements is computed independently. To prevent this, it is necessary to define a filtering radius, then averaging the sensitivity of all the elements within the sphere of influence [31].

Evolutionary Structural Optimization (ESO) methods

The ESO methods are close to the SIMP method, but they are of the "hard-kill" typology. Historically, the ESO method used a completely dense space domain as a starting point, and thence proceeded with removing the unnecessary material. In complete opposition there was the AESO method (Additive Evolutionary Structural Optimization).

In order to overcome the limitations of both algorithms, the BESO (where the B stands for Bidirectional) has been introduced. This technique adds and removes elements at the same time.

The objective function is represented by the mean compliance of the structure:

$$C(X) = \frac{1}{2}[F]^T[u]$$

Subjected to the constraints:

$$V^* - \sum_{e=1}^{N} V_e\, x_e = 0, \qquad x_e = \{0,1\}$$

F is the vector of external forces, while x_e is a binary variable, which represents the state of the element. As in SIMP, the filtering of the sensitivities must be used to avoid the checkerboard problem.

The initial volume is modified, using a value called ER, the Evolution Ratio. This quantity regulates the convergence towards the target volume V*. If the convergence criterion is not satisfied when the current volume equals V*, no further modifications of the volume are made, and the number of the added elements is the same as the number of the removed elements in the iteration.

Chapter 4
Modelling the existing part

The objective of the first phase of the project has been to simulate the mode of operation of the existing bracket in the best possible manner. Using the software Ansys, several analyses have been performed. The results of the analyses have been cyclically compared to the available experimental data, in order to refine the model at each step.
Being able to recreate the functioning of the bracket has been an essential passage to the validation of the three-dimensional geometries originating from the optimization process.
In particular three main analyses have been carried out: modal analysis, thermal-structural analysis and frequency response analysis.

Reproducing the constraints

Defining the best way of modelling the presence of the bolts has played a fundamental role in the three analyses. For this purpose, various configurations have been taken into account.
The bracket is simultaneously screwed to the engine head and to the Diesel Particulate Filter (DPF). In this last case it is necessary to point out that the two outmost holes are not directly linked to the filter, but to two little forks. These ones are then welded to the external case of the filter.

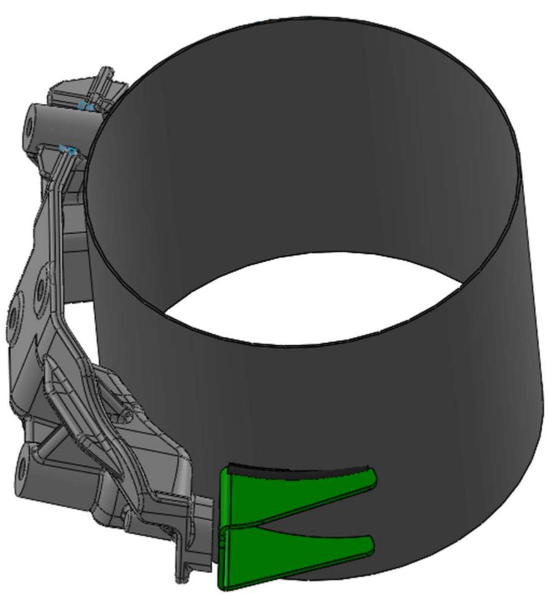


Figure 4-1: The initial bracket, mounted on the DPF shell.

The first considered possibility was the "Fixed support" command on Ansys. This option freezes all the degrees of freedom of all the nodes on a specified face. All the inner surfaces of the holes were selected. As a result, the model turned out to be over-constrained, and the first natural frequency was much higher than the expected value.

Moreover, it was not possible to differentiate the constraints of the holes connected to the DPF from the others. The same is true if the degrees of freedom are frozen exclusively for the nodes of the middle cross-section of the holes.

A better opportunity was to define the barycenter of each hole, then to connect all the nodes within the hole itself with the barycenter, through beams. At first, the lines have been drawn manually and CERIG elements have been used, i.e. analytically rigid elements. As in the previous case, the first natural frequency was greater than one order of magnitude than the real value. Unsatisfactory results have been obtain even connecting to the barycenter only the nodes of the middle section of the holes.

The solution to the problem has been found resorting to beam elements, varying the dimensions of the cross section of the beams.

Ansys's command "Remote displacement" is able to create all the necessary links automatically. Similarly, it is possible to connect the bracket to the barycenter of the DPF. The beams don't physically appear in the model. For this reason, topologic interpenetration issues are avoided.

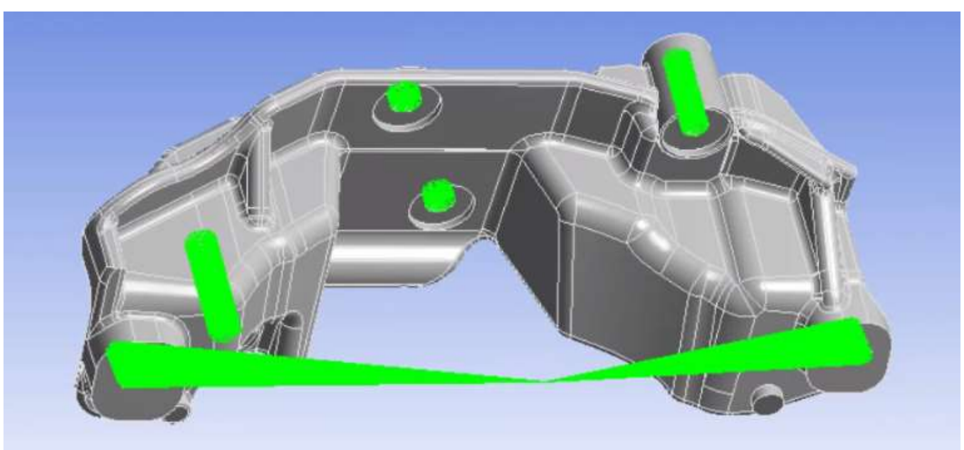


Figure 4-2: The beam used as constraints in the model.

Many different behaviors can be associated to the remote displacement command: rigid, deformable, coupled and beam. The only one which allows to select different values for the rigidity and for the radius is the beam one. In this way it was possible to regulate the dimensions of the beam, in order to approach the expected results. In all other cases, there is less room for maneuver.

All the beams used in the model have the same radius and the same material.

In the following screenshot it is possible to observe the definition of the Remote displacement command:

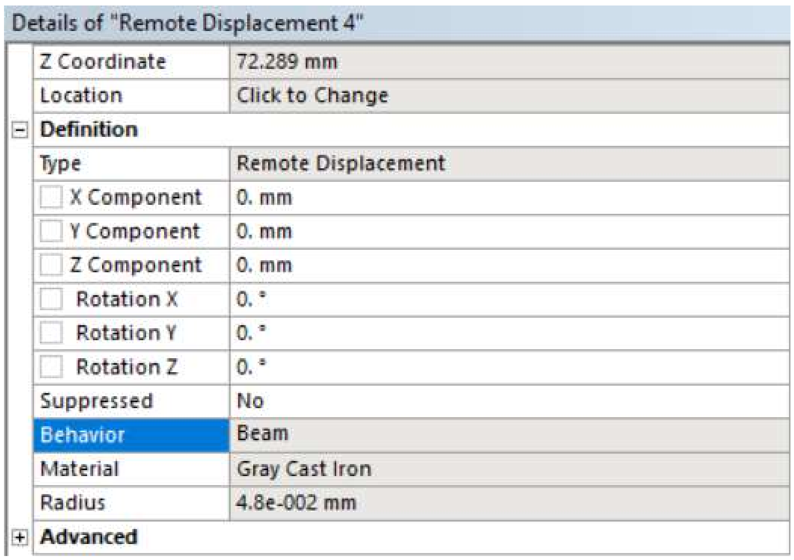


Figure 4-3: The definition of the Remote Displacement option on Ansys.

Among the advanced options, there is also the possibility of defining a “pinball” region, which allows to connect the barycenter of the holes with a larger area, and not directly with the nodes. This would prevent any discontinuity in the results. However, this opportunity was not used, because the results were already satisfactory, and no inconsistencies could be detected.

In the Table 4-1 it is possible to read the values of the first seven natural frequencies of the bracket:

Table 4-1: The first seven natural frequencies of the existing bracket resulting from the built model.

Mode	Natural frequency [Hz]
1st	250.66
2nd	400.9
3rd	506.86
4th	679.97
5th	759.14
6th	914.65
7th	1235.8

Thermal-Structural analysis

In order to carry out the Thermal-Structural analysis, it was necessary first of all to import the temperature distribution on the part.

Using the Static-Structural solver on Ansys, it is possible to set a single value of temperature for the entire body, but this is not sufficiently accurate. For this reason, before than resorting to the structural solver, it was necessary to use the Steady-State Thermal analysis. In this solver it is possible to assign different values of temperature on different faces of the body. Once the temperature distribution is computed, it can be used as an "imported load" for the structural analysis.

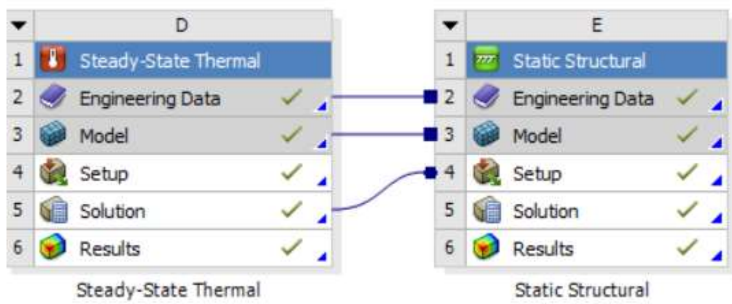


Figure 4-4: Conceptual links on Ansys.

The same configuration for the constraints of the modal analysis was used for the Thermal-Structural analysis, as well as the same mesh:

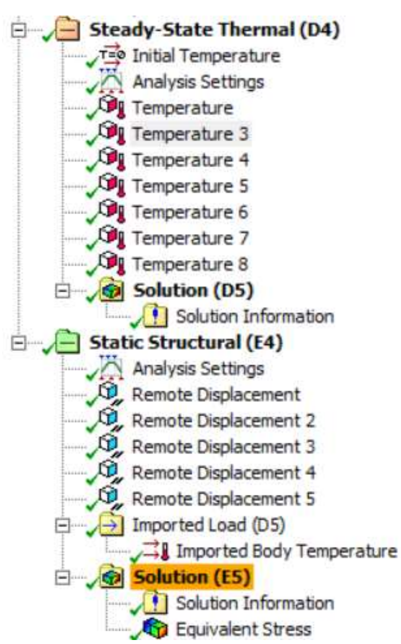


Figure 4-5: Some settings on Ansys

The used values of temperature were read from an image of the entire hot end, even if the inner surface of the bracket was not fully visible:

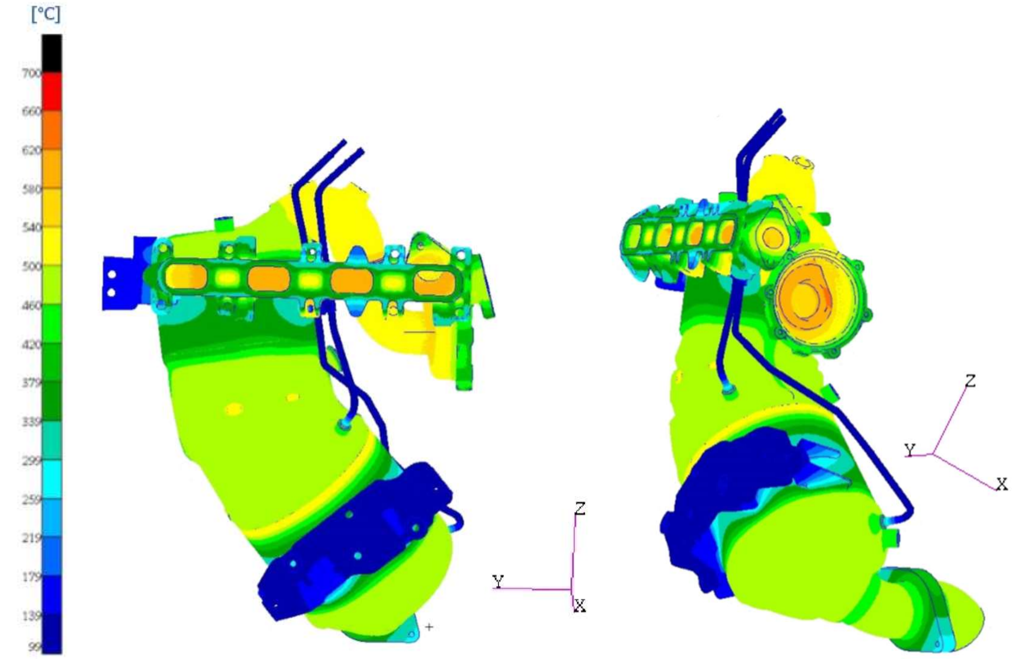


Figure 4-6: Temperature distribution in the hot-end. The bracket has a pronounced blue coloring.

In the Figure 4-7 it is possible to observe the expected stress distribution for the Thermal-Structural Analysis, computed with the Von Mises formula:

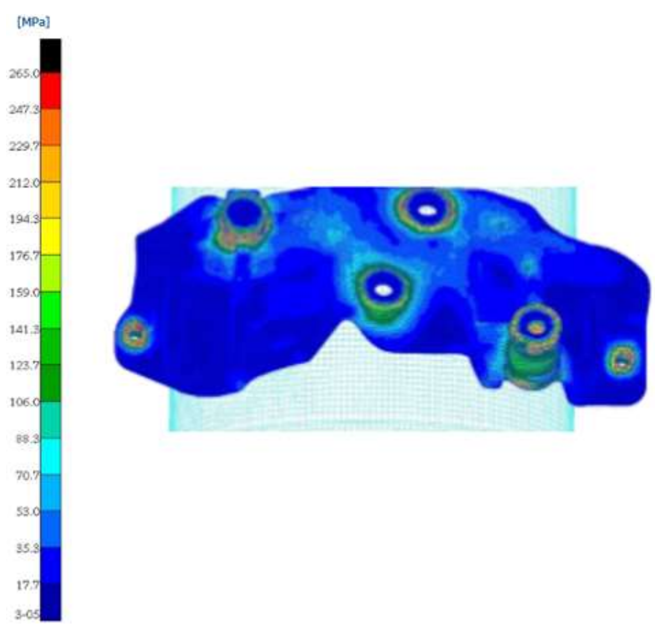


Figure 4-7: The expected stress distribution in the bracket.

In the Figure 4-8 it is possible to see the results coming from the built model:

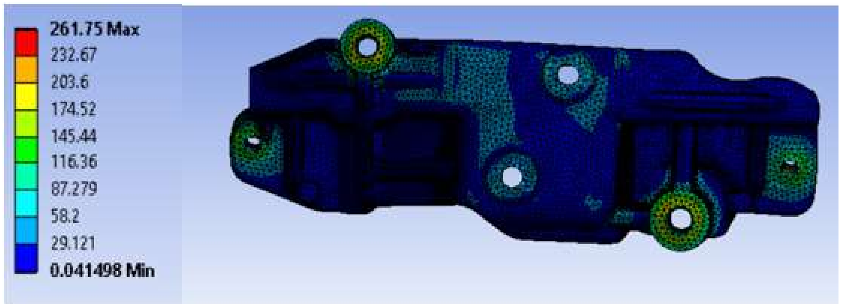


Figure 4-8: The stress distribution resulting from the built model

Frequency Response Analysis

The effects of the engine head displacements in the three Cartesian directions were studied in a frequency range between 30 Hz and 230 Hz. In Ansys, the displacements or the accelerations in input can be defined simply choosing a direction and the magnitude of the vector, or by means of the coordinates. In turn, the coordinates can be constant, or varying with the frequency. The input displacements were read from the following diagram, using a graph digitizer, which is able to recognize the different colors of the lines. The highest possible sampling frequency was set on the digitizer software.

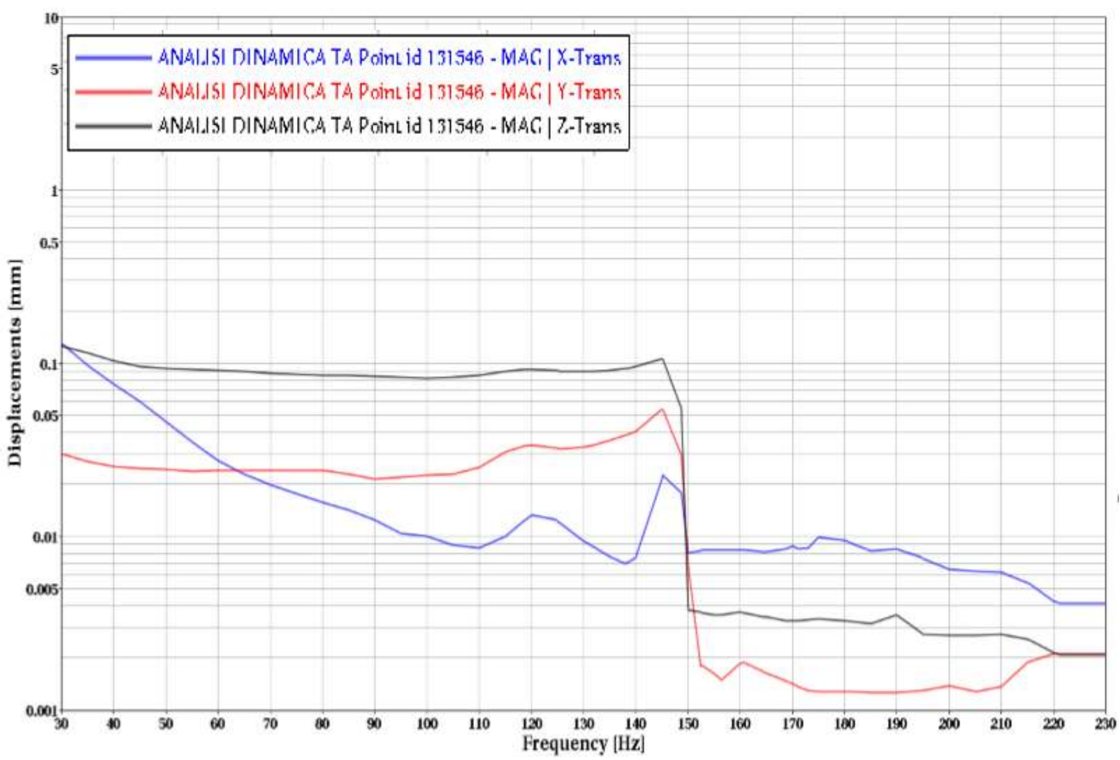


Figure 4-9: The displacements of the engine head in the three directions, varying with frequency

Nevertheless, the collected data for the X, Y and Z directions were not read at the same frequencies, while on Ansys the tabular values must be inserted at the same frequency. For this reason, it was necessary to employ MATLAB to interpolate in the frequencies of interest. The used command was `interp1`, which is defined as follows:

$$Vq = interp1(X,V,Xq)$$

Xq represents the query points, while Vq is the vector of the requested values.
In the Figure 4-10 it is possible to observe the expected stress distribution, computed at 145 Hz. This particular frequency is important because, as it is shown in Figure 4-9, the entire hot end resonates at that value.

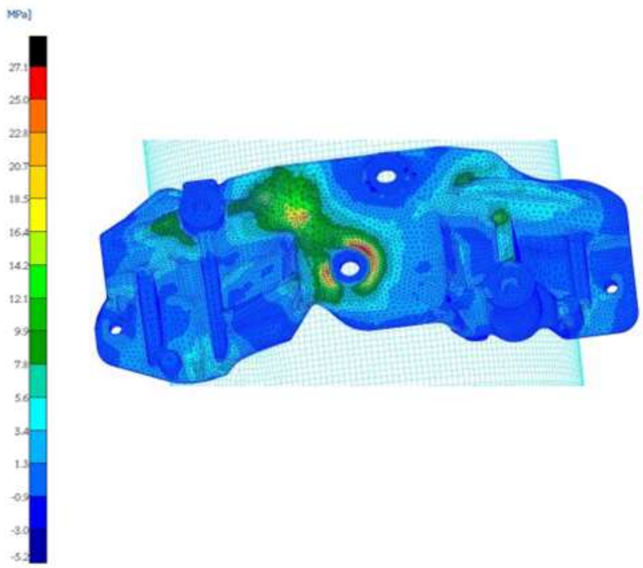


Figure 4-10: The expected stress distribution, computed at 145 Hz.

The following picture shows the stress distribution, obtained with the built model of the existing bracket.

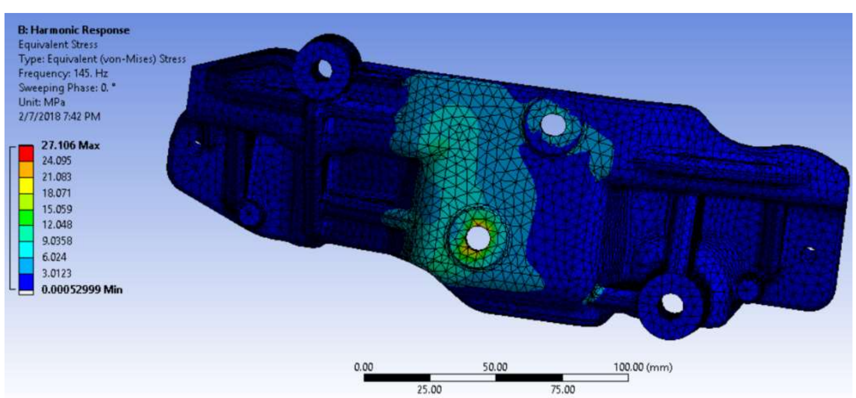


Figure 4-11: The stress distribution, resulting from the built model.

Chapter 5
Applying Topology Optimization: from theory to practice

Some applications of Topology Optimization for Selective Laser Melting have been published in the most recent scientific literature. Even if the first attempts did not frequently include the validation analysis through FE, nor an experimental validation, lately the papers have been starting to become more thorough on this subject.
In today's market, quite a few programs can implement Topology Optimization. They are generally accompanied by a simulation utility, in order to operate the modifications of the structure on the basis of previous analyses of different kinds. During the development of this thesis project three different programs have been considered, because of the availability of their software licenses: Ansys, Netfabb and SolidThinking Inspire.
Leaving aside a description of the well-known Ansys, a little introduction of the remaining two programs appears to be necessary, since they are normally known only by the "insiders" of designing for Additive Manufacturing.

Netfabb has been acquired by Autodesk in 2015. In addition to the Optimization and the Simulation utilities, which are available only in the Ultimate version, Netfabb works as well as a common software for the preparation for printing (such as the widely used Magics). It allows indeed to find the best positioning of the part on the building plate through dedicated scripts for packaging, to include the supports and to predict the building time. It is particularly efficient in the correction of damaged STL files, since it has numerous automatic repair scripts available. The Standard version of Netfabb is free for academic students.

Figure 5-1: Logo of the Autodesk software Netfabb.

SolidThinking Inspire belongs to the American company Altair Engineering, which is well known for the software HyperMesh. A little compatibility exists indeed between the two programs. Unlike Netfabb, Inspire cannot manage the printing preparation. However, a complementary version of Inspire, called SolidThinking Evolve is capable of performing extremely detailed operations on the elements of the triangular mesh.

Figure 5-2: Logo of the Altair software Inspire.

The main limitation of the programs which were born to execute Topology Optimization is that their simulation utility is somehow simplified, compared to the full range of possibilities offered by a complete computational environment such as Ansys. This means that even if Netfabb is even capable of optimizing lattice structures, the boundary conditions which can be imposed are only three: forces, pressures or restraints. There is no sign of thermal loads or of aspects related with the vibrational analysis. Furthermore, Netfabb insists on performing an automatic remeshing of the part, when this is transferred to the Optimization utility and this usually corresponds to a low-quality mesh, with extremely coarse elements.

Unlike Netfabb, SolidThinking is capable of including thermal loads, to impose sophisticated targets for the optimization and to consider different kinds of constraints and connectors.

One of the advantages of the dedicated programs is that they generally possess a well-stocked library, with the most common materials for Additive Manufacturing. Moreover, on Netfabb it is not necessary to import manually the dimensions of the building plate, since they can be chosen directly from a list of commercial models.

Ansys has recently included the Topology Optimization solver among its variegated abilities. It can be used starting from various environments, such as structural analysis or modal analysis. A newly formed joint solver is even capable of implementing the optimization precepts starting from thermo-fluid dynamic analyses. As mentioned earlier, with Ansys the analyses can be set in a far more precise way than with the other two programs and there is also a complete control on the quality of the mesh. The most important limitation of Ansys is the almost totally absent attention to the manufacturability requirements. In order to understand these limitations, it is necessary to describe the procedure followed to set the optimization computations.

In order to perform Topology Optimization, once the initial model of the part has been fine-tuned, the first item on the agenda is to define the design region and consequently the excluded region. This is the portion of the part which cannot be modified by the solver. In the specific case of the bracket, all the holes have been assigned to this region. More generally, all the portions which form a coupling with other mechanical components should be omitted from the design space. On Ansys it is possible to select the excluded faces directly on the program, while this is not possible on SolidThinking Inspire.

For this reason, it has been necessary to cut manually the hole regions on a three-dimensional CAD software, such as SolidWorks. In the Figure 5-3 it is possible to see the part as it looks when it was transferred to SolidThinking:

Figure 5-3: Definition of the design region (red colored) and of the excluded region (grey colored).

The design space is red-colored, while the grey parts represent the excluded region.

At this point it is necessary to define the strategy and the constraints. For instance, on SolidThinking there are two different objectives which can be selected: maximizing stiffness or minimizing mass. In the first case it is possible to set a certain mass target, while in the second one a minimum safety factor can be selected. In both cases a constraint on the frequency and a limitation on the minimum and on the maxim thickness of the resulting part can be imposed.

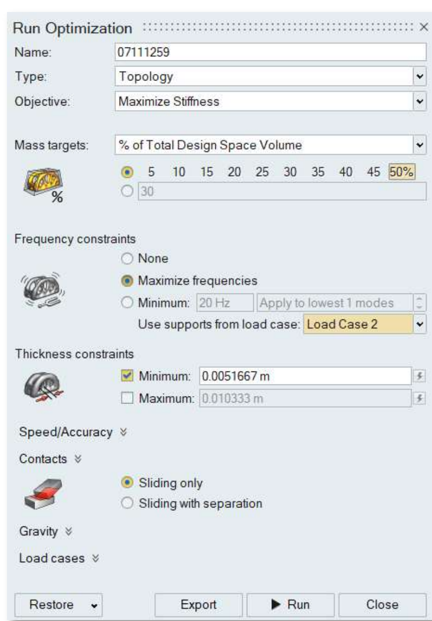


Figure 5-4: The preparation of the optimization.

In the following image the results corresponding to the settings showed in Figure 5-4 can be observed:

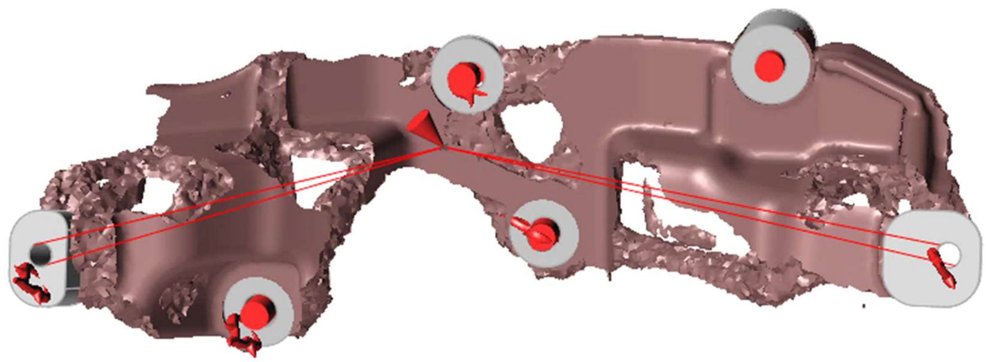


Figure 5-5: An unsmoothed part obtained with SolidThinking.

The parts resulting from Ansys present in almost all cases some detached parts. Some of the holes are completely separated from the rest of the body, resulting in a completely meaningless geometry. Ansys possesses also a direct link to a validation system of the results, but it cannot handle the complex geometries resulting from the Topology Optimization and therefore is actually unusable.
The procedure which has been followed during this thesis project started with the SolidThinking solver, then it continued with the validation analysis with Ansys.

The STL file format

At present, most of the optimization programs allow to export the results of the computations only in a non-CAD format, such as a STL file. This genre of file format is really common in several applications, first of all Additive Manufacturing, but for instance it can also be applied for Numerical Control Machines. Indeed, several advantages are available, such as the simplicity of the code and the portability.
Various meanings have been attributed to the acronym STL (STereoLithography, Solid To Layer, etc.), but without doubt the most evoking one is “Standard Triangle Language”. Indeed, the part is converted into a surface mesh composed by triangles, whose coordinates are saved into the file. The order in which the vertexes are enumerated is fundamental for the definition of the sense of the normal vector to the surface, in accordance with the right-hand rule. The normal vector enables to distinguish the filled domain from the empty surrounding space.

Here is an example of the STL code in ASCII language:

```
facet normal ni nj nk
        outer loop
            vertex v1x v1y v1z
            vertex v2x v2y v2z
            vertex v3x v3y v3z
        endloop
endfacet
```

Since ASCII files can become really large, a binary version of the STL file format also exists.

It is possible to point out numerous negative aspects of this file format: first of all, a certain redundancy of information. It is not necessary to specify the vectorial components of the normal vector, since they can be computed from the vertexes of the triangles.
A second point to consider is that the coordinates of the vertexes must be repeated several times for each triangle which shares the vertex. This may introduce leaks and rounding errors, which need to be fixed with repairing algorithms [32].
A CAD file is without doubt something more complex, because it is an accurate mathematical representation of a geometry. This means that every line or every surface is approximated by a Bezier curve or a NURBS.
Generally, when a STL file is forced to become a CAD file, the surfaces of the triangles are not merged into a bigger surface, but they are interpolated singularly. This operation leads to really heavy CAD files, which are not at all easy to manage. It has been possible to observe a high percentage of failure even with a famous software such as SolidWorks, in converting a geometry as complex as the considered bracket. On the contrary, the transformation is less laborious for simple geometries.
Since this file format is accepted by all 3D printing machines, the STL format has become the *de facto* standard for this group of manufacturing technologies. Other common file types for AM are AMF, 3MF, OBJ or PLY.
These other options were developed because of the fact that the STL file format is almost 30 years old and it did not keep pace with the huge advances in the machines. Only some little updates have been introduced, such as the possibility of saving the colors of the part.

In 2011 the international standards organization ASTM released the XML-based file format AMF (the acronym stands for Additive Manufacturing File Format). It contemplates a lot of details which were not available in the STL file, such as colors, texture, materials and it also allows to combine objects into a certain pattern for printing. An interesting peculiarity of the AMF is the introduction of curved triangles, which allow to reduce the discretization error of a spherical surface by a factor of 1000, in comparison to the same surface, described by the same number of planar triangles [33].

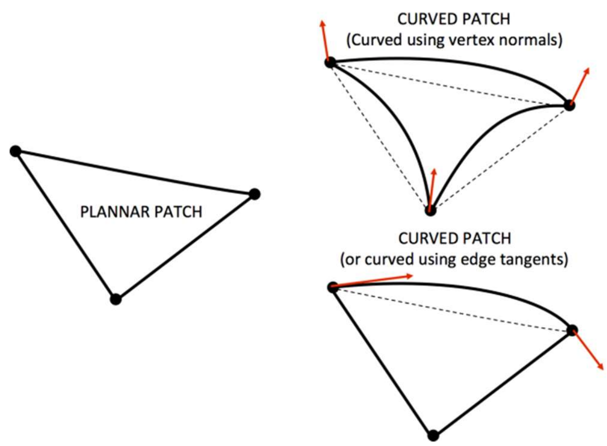


Figure 5-6: Curved triangle patch in AMF format. Reprinted from [34].

Even if two years later after its birth (ISO/ASTM 52915:2013) it was chosen as the official standard for 3D printing, it never had the hoped commercial success, mainly because of its complexity. Given the low demand, the AMF is supported only by high-end machines.

In order to obtain a more manageable file, the 3MF Consortium was founded in 2015. It is composed by the most important companies in AM and not just them: Autodesk, Dassault Systèmes, HP, Microsoft, SLM Solutions et cetera. The abovementioned 3MF file format is really similar to the AMF one, also because it is XML-based as well, but obviously not identical. For example, the possibility of using curved triangles is not available in the 3MF type.

The 3MF should be intended as a middle way between the STL and the AMF.

The OBJ file type must be seen instead as a rendering format, with particular emphasis on effects such as lightning and fog, but it was not designed for manufacturing.

The smoothening process of the STL files

The results generated from the Topology Optimization software are characterized by high superficial roughness. This condition is generally not suitable for the manufacturability or for the validation analyses, and even less for the utilization of the mechanical part.

Therefore, interpreting the results is of the outmost importance and in particular, applying smoothening algorithms.

The same problem affects complex geometries, such as from biomedical applications, which are digitized with laser or with tactile scanners (Reverse Engineering). The cloud of points deriving from the scanning can be in fact re-elaborated in order to obtain a surface mesh, e.g. a mesh of triangles.

A common approach is using the Laplacian smoothing, which is supported by a simple idea: the location of the vertexes is substituted with a new position, computed by averaging the coordinates of the neighboring nodes.

The Autodesk software Netfabb, for instance, is equipped with a smoothening utility, but the dimensions and the tolerances are not maintained, because of deformation and shrinkage. The same holds true for every software which uses the standard Laplacian algorithm, and which applies it to the entire part.

The free software Meshlab, on the contrary, allows to select manually the regions to whom applying the algorithm. In detail, the used procedure is based on a paper from Vollmer, Menci and Müller.

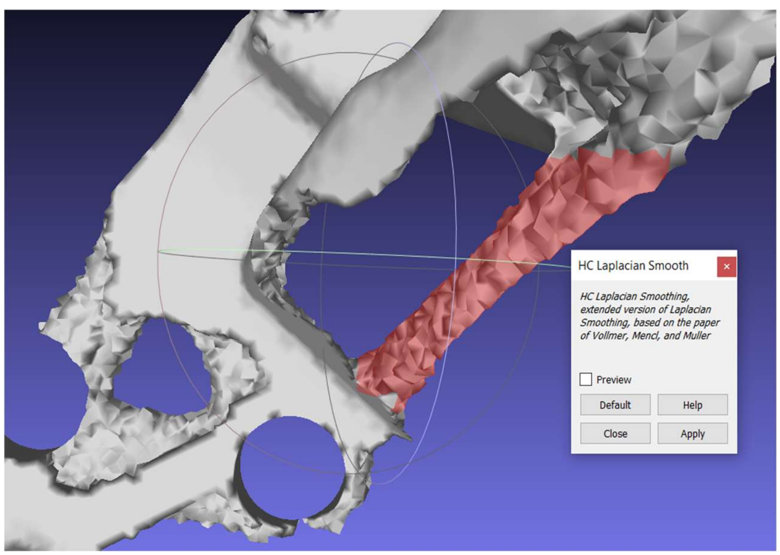


Figure 5-7: Applying the smoothening algorithm to selected regions.

The traditional Laplacian algorithm can be mathematically written down in this way:

$$p_i := \begin{cases} \dfrac{1}{|adj(i)|} \sum_{j \in adj(i)} q_{j,} & i \in V_{var,} \\ q_{i,} & i \in V_{fix}. \end{cases}$$

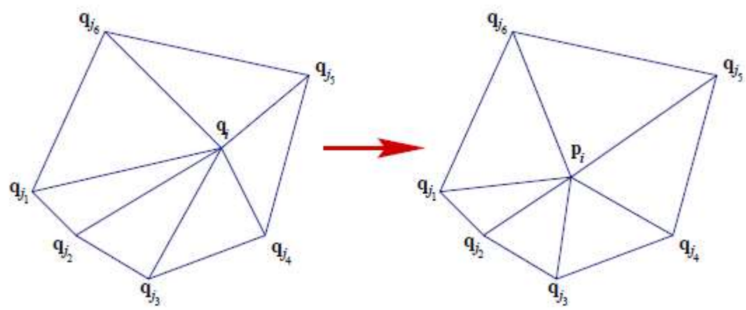


Figure 5-8: Consecutive steps in traditional Laplacian algorithm. Reprinted from [35].

V represents the set of nodes which constitute the mesh and it can be divided into a subset of fixed nodes and in a subset of variable nodes (V_{var} and V_{fix}, respectively). The function p: $V \rightarrow R^3$ correlates the vertexes to their coordinates in the space. The set of adjacent nodes to q_i is denoted as adj(i).

As it is known, the Laplacian algorithm does not converge in all situations; therefore, some modifications have been proposed. Firstly, it possible to observe that the position of the central point q_i is not included in the computation. Nonetheless this variation of the original Laplacian algorithm does not improve the final result of the smoothening, nor prevents the shrinkage, but it only delays the process.

A better idea is to take into account the original points o_i, weighted through a parameter α, and not the central point:

$$p_i := \begin{cases} \alpha o_i + \dfrac{1-\alpha}{|adj(i)|} \sum_{j \in adj(i)} q_{j,} & i \in V_{var,} \\ q_{i,} & i \in V_{fix}. \end{cases}$$

The convergence is guaranteed if $\alpha > 0$. To use this version of the Laplacian algorithm, it is necessary to find a value of the coefficient α which ensures at least an adequate compromise between the smoothing quality and the deformation of the geometry.

An alternative to Laplacian smoothing can be represented by the HC algorithms (HC stands for Humphrey's Classes) [34]. In this case the idea is to take back again the modified points p_i toward the original q_i, on the basis of the average of the differences b_i. Nevertheless, it is necessary to execute a given smoothening algorithm as a first step.

$$b_i := p_i - (\alpha o_i + (1-\alpha) q_i)$$

$$d_i := -\frac{1}{|adj(i)|} \sum_{j \in adj(i)} b_j.$$

The HC algorithm leads to far more efficient results, even if not completely free from shrinkage.

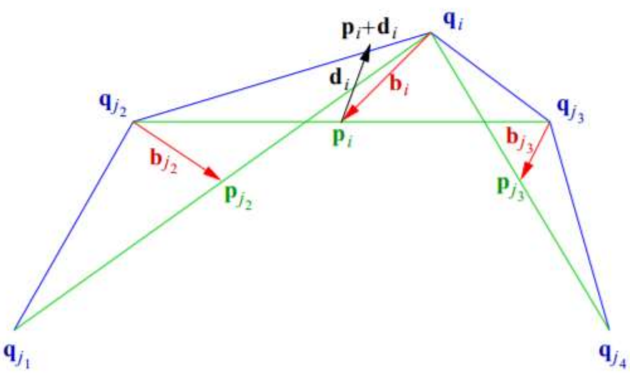


Figure 5-9: The HC smoothening algorithm. Reprinted from [35].

A major contribution in the smoothening process has been provided by the remeshing, which has been executed on Netfabb. At the very beginning it was performed because of the necessity of homogenizing the element size of the triangle mesh, which was completely scattered after some interventions on the drawing. As a matter of fact, it is possible to note that having a refined and uniform mesh leads to better results in the smoothening process.

When a certain number of surrounding triangles are selected to perform the HC algorithm, if these considered triangles are too large, the consequent shrinkage may affect larger areas.

In the following example the goal was to incorporate an extruded portion, drawn on the CAD, in the entire part, avoiding in this way the presence of steps. The Figure 5-10 shows the initial condition:

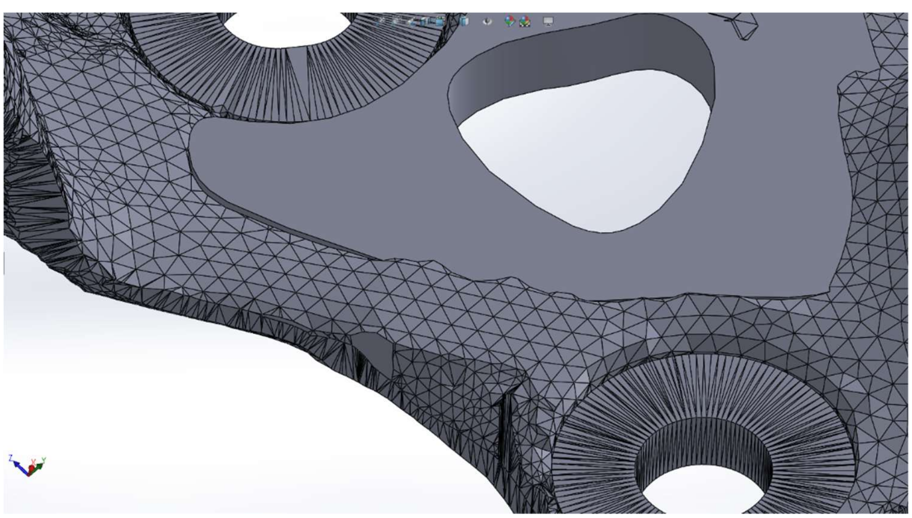


Figure 5-10: Modifying the STL file on SolidWorks.

The extruded part is highly identifiable, because in the software it had not yet been meshed. These CAD interventions were necessary to fill some holes, or to reconstruct completely some regions, which even after the smoothening process hadn't reached a satisfactory shape. In the showed example, the reason of this operation was to improve the curvature of the central opening, in order to "soften" the entire area.

The following images show the initial mesh with uneven triangles and the resulting deformation which affects the edge of the central opening.

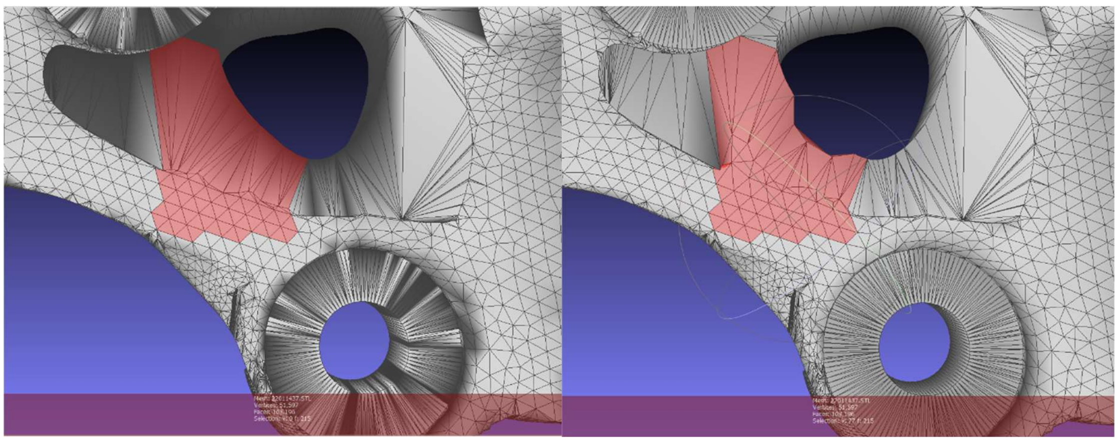


Figure 5-11: The effects of the smoothening algorithm on a coarse mesh.

On the other hand, starting from a refined mesh, it was possible to limit the effects of the algorithm in a more confined region, avoiding undesirable effects. The remeshing performed on Netfabb had already contributed in the integration between the two parts, as it is possible to observe in the Figure 5-12:

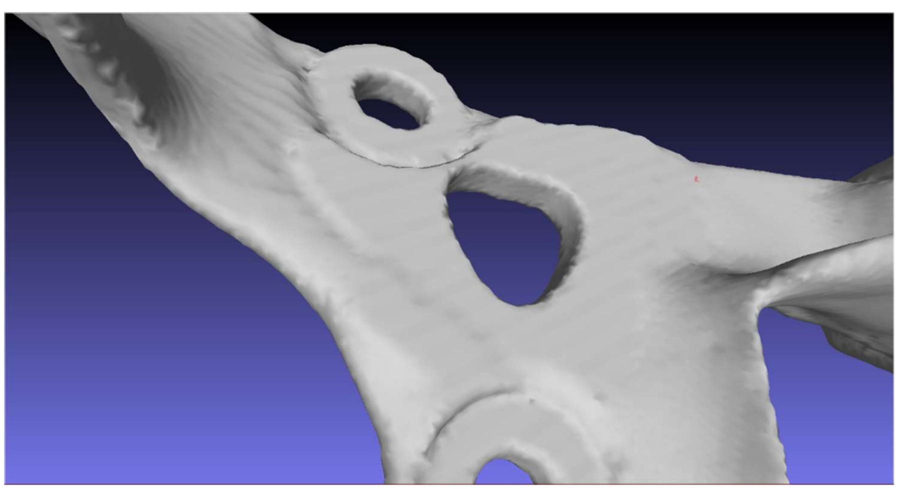


Figure 5-12: The result of a remeshing on Netfabb.

With a finer and homogeneous mesh, the triangles could be selected with much more attention:

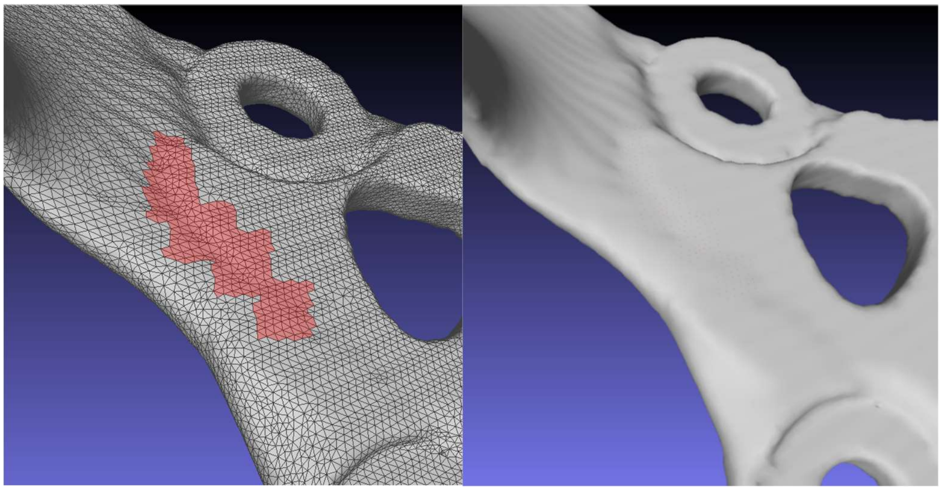


Figure 5-13: Executing the smoothening on a finer mesh.

The remeshing contributes also to rounding off the features, which is not at all unwanted. The regions of the part which used to belong to the excluded region in the previous analyses can be simply re-merged, for the purpose of having well shaped holes.

The remeshing- along with repair algorithms- is resolvent for another problem which appears sometimes when the smoothening is performed. In practice, when a little indentation is smoothed, it may happen that it starts to extend in depth. This problem is not easy to be detected, unless a cross-section of the part is observed.

A better strategy to find these problems and others of this sort is to consider the cross section of the STL file, which contains only the external shell of the part. In this situation, these indentations are showed as filled elements in the interior of the part. Alternatively, it may be useful to visualize the part in the wireframe modality, because any problem of this kind will correspond to a greater density of lines. In the following example, the error was present since the topology optimization.

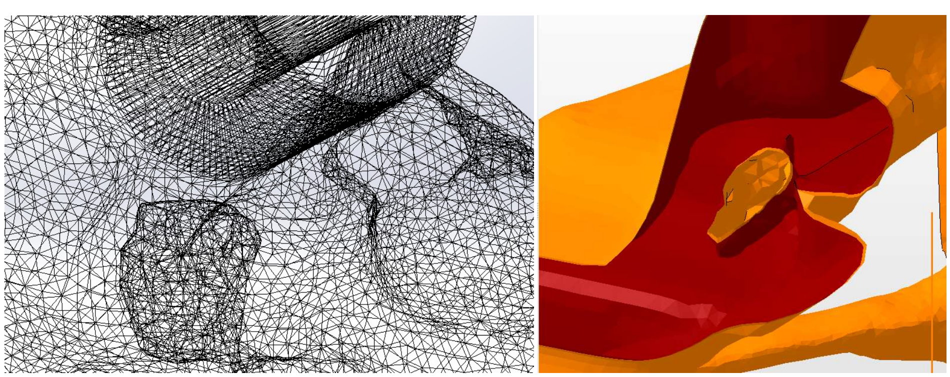


Figure 5-14: Some issues in the STL file.

Chapter 6
Validating the optimized part

In order to validate the results originating by the Topology Optimization program, the model built on the basis of the functioning of the initial bracket was used. The mesh was obtained with the help of the program HyperMesh. After some final adjustments (some self-intersections were detected), the element size was chosen equal to that used for the original part. Once the surface triangular mesh was computed, the tetrahedral solid mesh was created.

The model thus obtained was then transferred to Ansys for the performance of the analyses, as it is possible to observe in the Figure 6-1. The material properties of the Maraging Steel, as declared by the powder supplier, have been entered. In particular, the characteristics of the as-built material have been considered, in other words without taking into account any sort of heat treatment.

It is possible to affirm that the redesigned bracket is 40% lighter than the of the original one.

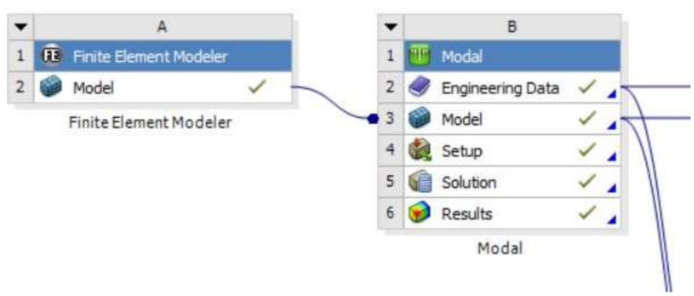


Figure 6-1: Importing the mesh on Ansys.

Modal Analysis

The same constraints of the built model are used. The beams have the same cross section and the same mechanical properties.

The Table 6-1 shows the values of the first seven natural frequencies resulting from the simulation. Then first natural frequency is higher than 250 Hz, as a result of the substantial mass reduction. Therefore, it is possible to affirm that the initial goal of decoupling the functioning of the bracket and the frequency range of the engine head vibrations was achieved.

Table 6-1: The first seven natural frequencies of the redesigned bracket resulting from the built model.

Mode	Natural frequency [Hz]
1st	310.61
2nd	404.7

3rd	576.63
4th	686.04
5th	752.44
6th	839.93
7th	1131.4

Thermal-Structural Analysis

In figure 6-2 it is possible to observe the stress distribution of the redesigned bracket. The equivalent stresses were computed using the Von Mises formula. Obviously, the same temperature distribution was used.

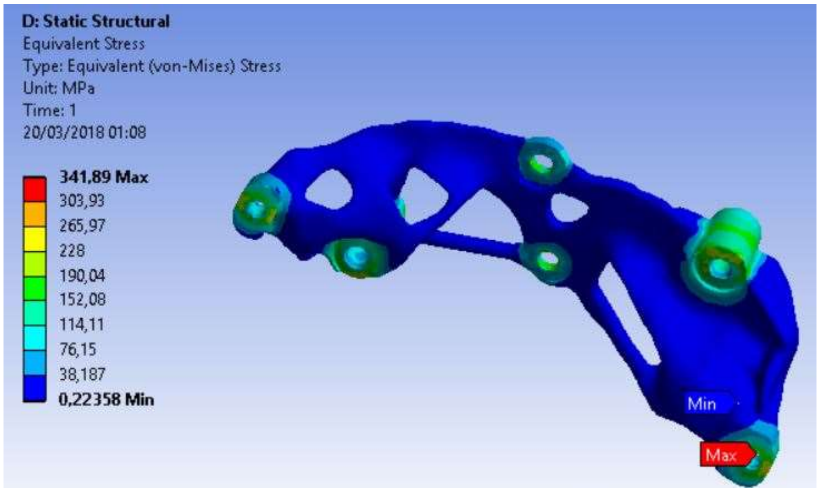


Figure 6-2: The stress distribution of the redesigned bracket resulting from the built model.

The maximum computed stress is much lower than the declared Yield strength.

Frequency Response Analysis

In the following image the equivalent stress distribution of the Frequency Response Analysis can be observed.

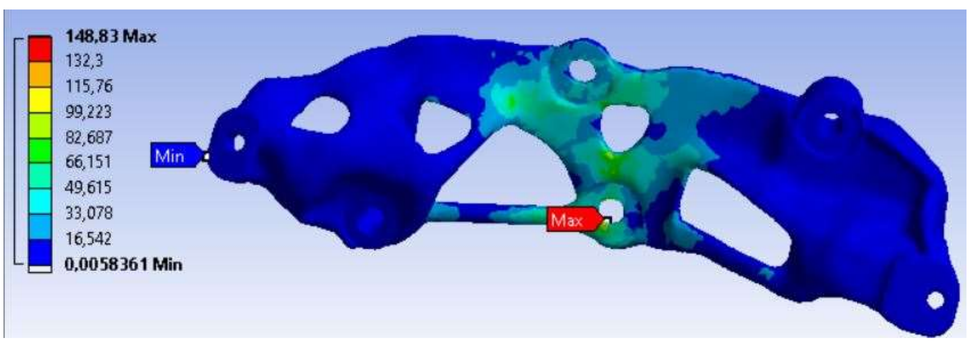


Figure 6-3: The stress distribution of the redesigned bracket resulting from the built model.

Chapter 7
Building the part

As a matter of fact, dealing with large parts is significantly different than printing some samples or little coupons. The main difficulties are due to the fact that the energy distribution of the laser beam may be significantly different compared to that of simple geometrical parts, such as cubes or cylinders. For this reason, the process parameters used normally for research purposes may not be suitable for printing functioning full-scale mechanical components.

Another problem related to printing large parts is that since samples sometimes cannot be completely representative of the actual process, a trial and error method is almost indispensable. This can be extremely time-wasting and expensive, especially when the part requires many hours to be completed, or when it is not possible to fit more than one part on the same building plate.

Many other issues may not even be perfectly detected before than starting to print.

Building process simulation

The process simulation, along with the product simulation, has played a fundamental role as a support to the production activities in the last decades. Although it was initially considered something “extravagant”, which needed powerful calculators, and which used extremely simplified models, the so-called CAE (Computer Aided Engineering) programs nowadays accompany every moment of the design. The process simulation is central in the modelling of manufacturing technologies of all kinds- injection molding, metal forging, machining et cetera- and it can be developed with general purpose software or with dedicated software. Some of these programs are currently available in the student version for free and are taught in the Engineering classes, since their knowledge appear more and more among the recruitment preferential requirements of several industrial companies.

In addition to this, it must be remembered that the idea of simulating every stage of the production cycle is one of the cornerstones of Industry 4.0 [35].

Like stated previously, Netfabb has at its disposal a Simulation Utility, which is capable of simulating accurately the building process. It is not just about computing the building time or defining the best positioning of the part on the plate, as a normal pre-processing software would do.

In addition to Netfabb (which was actually available in the research lab), many other simulation programs for Additive Manufacturing have been developed in the most recent years. Among them, 3DSIM, which is now part of the computational environment Ansys, the program ESI Solutions and the program Amphyon of the German company Additive Works GmbH (sponsored also by European Union).
As stated above, the simulation can be set up in a general-purpose software: for example, at present some companies still use Abaqus to predict the behavior of a metal in the die during the stamping. Certain others rely on specific programs- QForm, to name but one according to the previous example- thus using user-friendly applications, which may even be employed by not too specialized staff. The greatest advantage of building the model from scratch is the possibility of managing some aspects which are almost completely hidden beneath the graphic interface, such as meshing strategies or statistics or several mathematical aspects. On the other hand, a dedicated software contains already all the necessary data which are required to perform effective simulations, e.g. specific material libraries or details on the machines.

It can be said that the overall concept is shared by all of the aforementioned programs: to simulate an Additive Manufacturing process for metals in an effective manner, it is indispensable to use a multiphysics approach. Firstly, the thermophysical properties of the material should be taken into account: thermal conductivity, emissivity, specific heat, friction, density, thermal expansion coefficient, absorptivity and so on.
Then, the effects of the powder features on the actual material properties should be considered: average size, morphology, chemical composition, oxidation (when the powder is recycled).
Of course, the process parameters or other processing features cannot be neglected in this analysis, nor the energy source type (laser or electron beam). In this way, the presence of vaporization and the effects of the melt pool topology, can be contemplated too.
All of this is fundamental to the description of the thermal history of the part, because this plays without any doubt the decisive role in the generation of a specific microstructure, of a phase transformation, of localized residual stresses [36].
In particular, Netfabb takes into account several variables simultaneously, such as the process parameters used in a specified machine with a specified material. It allows to consider the preheating of the building plate and its possible deformation, but also it predicts the effects of a heat treatment after the building process. Netfabb is able as well to simulate both “powder-bed” and “direct” technologies for metals.

The support failure prediction is one of the most interesting capabilities of this utility. Indeed, it happens really frequently that the failure of an entire build is due to the inadequacy of the supports in some problematic areas, such as connections between curved regions.
Netfabb also computes the expected deformation of the part, due to residual stresses. This information can be used as well to obtain a new geometry with some corrections. In other words, the differences between the printed part and the CAD model are prevented by imposing a displacement in the opposite direction, which counterbalances the undesired deformation. Thus, the obtained STL can be used for the actual printing process.
It must be pointed out that the Netfabb Simulation Utility is brand new and the services provided are continuously growing and sometimes they need a better calibration. It doesn't make either suggestions on how to change the supports, for the purpose of preventing their failure. A trial and error method must be used.
At a certain stage, the simulation with Netfabb was not actually used for two main reasons. The first one is that the Maraging Steel was not among the available ones in the library of the software, although it is a really common material for SLM. Despite the fact that it is possible to import a new material, as stated above, the required data are extremely numerous and precise. As can be seen in the following image, the values of conductivity, elastic modulus, emissivity, et cetera, should be inserted at different values of temperature. Neither the producers of the powder, nor the software developers share those data, not even after seeking the help of the customer service. An experimental analysis would be therefore necessary, before than starting using the simulation properly.

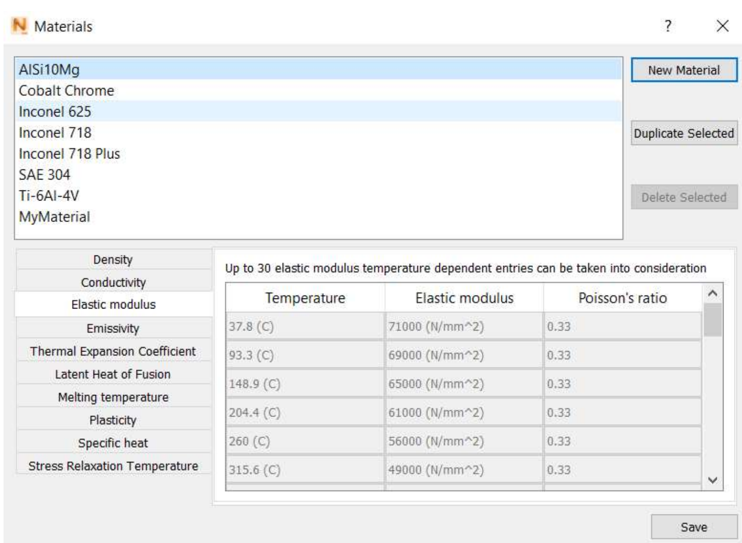


Figure 7-1: The large amount of data necessary to perform the process simulation on Netfabb.

The second reason is that the process parameters used during the printing cannot be changed from the standard ones, unless a different license is used (Autodesk Netfabb Local Simulation). The point is that when it comes to a new material, the standard process parameters are not inserted as well and there is no way to add them, even if they are known from different sources (the possession of the machine). The PRM file (Process ParaMeters) which should be imported is written in an encrypted code. Therefore, there is no way to carry out a simulation taking into account a new material, unless using the extended license.

Going back to the general current state of play in the process simulation, countless arrangements need still to be made. A difficult challenge is represented by the modelling of the melting pool behavior. Initially it was handled by using the same instruments used for the simulation of welding, but this makes it impossible to treat some relevant phenomena for AM. A more detailed model would be capable of estimating more precisely the cooling rates, or some effects due to the surface tension.

As regards the powder properties and their actual effects on the printed parts, it must be kept in mind that some of these aspects are still not completely understood and they are still contentious research topics.

At the moment there is not either the possibility of predicting the surface finish, except for some overly-simplistic attempts.

Some of the challenges in AM simulation will be won only by running an extremely large number of tests and by experimentally validating the results from the code.

What really counts is to find a good compromise between having a fairly detailed analysis and limiting the computation time.

Description of the equipment for the printing

The machined used to build the part is a EOSINT 280, produced by the German company EOS GmbH. Designed as an updated version of the EOSINT 270, it was recently substituted by the 290 version and it is not anymore available for sale (although a second-hand market has become flourishing since then).

The building volume is 250 mm x 250 mm x 325 mm and the used laser is a Yb-fibre laser, with a power of 200 or 400 W. The scan speed can be increased up to 7 m/s and the focus diameter may vary from 100 to 500 μm.

As already stated before, the utilized powder was purchased from the machine producer. More than 130 kg of powder were made available for the tests. A large part of them was constituted by virgin powder, which was mixed up with the recycled one at a certain stage.

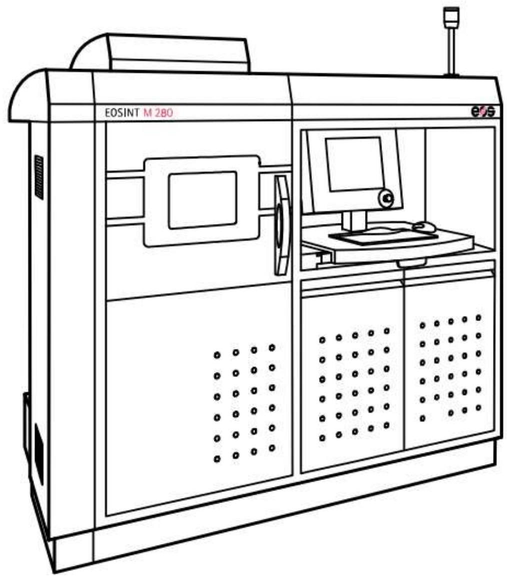


Figure 7-2: A drawing of the EOS M 280.

Building preparation: the software side

A long procedure must be followed before than starting to print. First of all, it is necessary to import the STL file in the software Materialise Magics, in order to generate the supports. The version which was used is 20.04.

The part was placed diagonally across the building plate, because of the limits in the dimensions. Indeed, the dimensions of the building plate of the used machine are 250x250 mm, while the bracket is 260 mm long.

For this same reason, it wasn't possible to fit more than one part on the building plate. Nevertheless, some coupons were added in some of the prints for other purposes.

Various positionings of the part on the building plate have been investigated. The idea of positioning the part completely perpendicular or tilted compared to the base was rejected from the beginning, because of the long time required to complete the process and because of the really large amount of needed powder. Using a big amount of powder is not always an optimal choice, also because it will correspond to a longer amount of time needed to sieve and because a bigger amount of powder at the end will be considered as "for recycling".

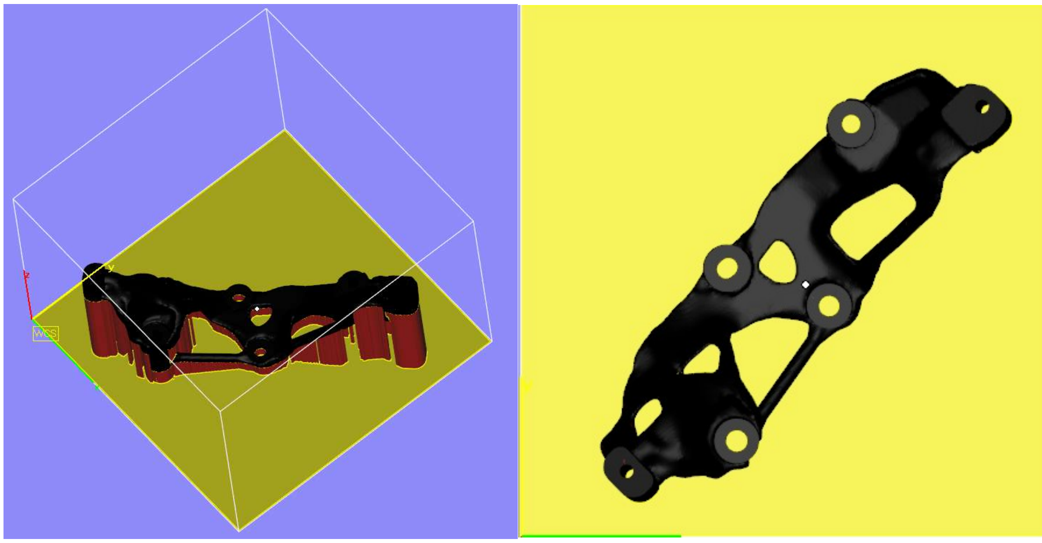


Figure 7-3: Finding the best positioning on the building plate, using Magics.

The software which allows to monitor the process and to control the EOS machine while it is running is called PSW 3.8 (the name stands for "Process SoftWare). The file loaded on this platform must be in the SLI file format (Slice Layer Interface). This means that the parts and the supports must be already divided into slices. There are many ways to convert the STL files to the SLI format, but the suggested procedure was followed.

First of all, once the supports were created and checked on Magics, the part was saved again as an STL file (in order to maintain the chosen positioning), while the generated supports were saved as an CLI file. CLI stands for "Common Layer Interface".

These two new files were then moved to the software RP Tools, where they were transformed into two SLI files, after the 40 μm layer thickness was selected.

Once the SLI files were loaded on PSW, it was possible to define the process parameters. In particular, different process parameters were used for the part, the supports and for the initial exposure of the building plate, after the first layer is deposited. The job was then saved and moved to the computer of machine.

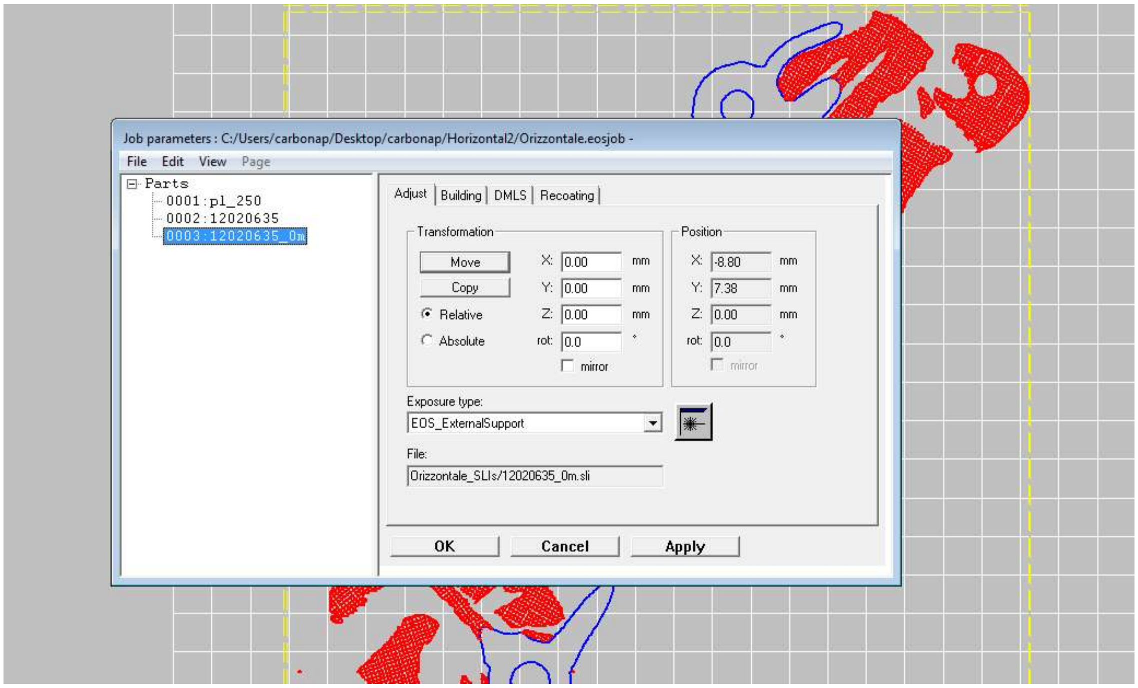


Figure 7-4: Defining the process parameters on the software PSW.

It is important to evaluate the amount of powder which is necessary to print. As is well known, the building plate must be completely filled with powder at each layer. For this reason, a rough estimate may be computed simply multiplying the dimensions of the cross section of the plate by the height of the part, according to the chosen positioning and then considering the density of the material:

$$q = A_{building\ plate} \cdot h_{part} \cdot \rho_{material}$$

Although this simple formula is suggested by the machine producers, it doesn't take into account the overfeeding parameter. This means that the machine spreads more than the necessary powder on the building plate. As a result, much powder is simply discharged in the collector, without remaining on the plate, because the layer thickness must remain unchanged, regardless of the overfeeding parameter.

A certain amount of powder must be considered anyway to properly carry out the leveling operations. A little "safety factor" is therefore suggested.

The suggested formula should be modified as follows:

$$q = A_{building\ plate} \cdot h_{part} \cdot \rho_{material} \cdot overfeeding \cdot SF$$

The value set in the machine was remarkably high and extremely cautious (300%), but since it was the first time that the machine was used to build such a high part, nobody was fully aware of this. Some of the EOS users suggest a value of about 130%.

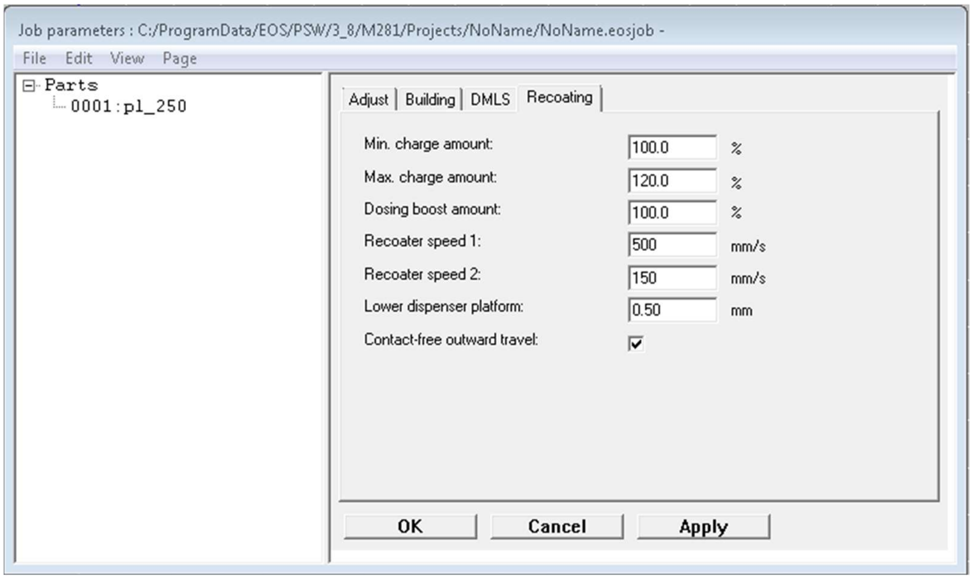


Figure 7-5: The definition of the overfeeding parameter.

In order to understand why the set value of the overfeeding parameter had no practical meaning, an example will be given. The height of the bracket on the building plate is equal to about 10 cm, while the density of the Maraging Steel is equal to 8.1 g/cm^3. The quantity of necessary powder, computed according to the previous formula is:

$$q = 625\ [cm^2] \cdot 10.0\ [cm] \cdot 8.1 \left[\frac{g}{cm^3}\right] = 50.6\ [kg]$$

Because of the initial overfeeding parameter, the actual necessary powder should have been equal to 151.8 kg, which is tremendously high, given that the printed part weighs only 1.2 kg and that no more than one part can be built at a time. This would correspond to an enormous tied up capital.

The machine has not an automatic system for recycling powder while the process is running. For this reason, if all the necessary powder is not stored in the reservoir at the beginning, there will be an interruption of the process, and this will result in a lot of powder to be discarded. In fact, once the process chamber door is opened, the inert atmosphere inside the machine is lost, as well as the temperature conditions.

The overfeeding parameter can be even slightly reduced throughout the printing. It may happen that at a certain point of the process the portion of the building plate which still needs to be manufactured is located on the left side (in the EOS machine the powder is arranged from right to left). Since the laser exposure will affect only that part of the plate, it is not necessary to deposit the powder on the entire plate.

Building preparation: the practical side

After a quick cleanup of the process chamber, it is necessary to sieve the powder for the printing. A large quantity of powder was sieved, because of the height of the part in the chosen positioning, even if a big amount of it was not actually subjected to the laser beam.

The manual sieving of the powder is a long process, which requires also a regular removal of the burnt powder. As a matter of fact, if the sieving is not executed properly and the sieve is not emptied from time to time, the oxidized particles may be forced through the mesh of the sieve. The EOS machine available for the project is not equipped with an automatic sieving system; therefore, this operation must be executed manually.

After mounting the building plate, it is necessary to carry out the leveling of the system. This procedure needs to be executed as well by hand and it happens with the door of the chamber fastened. The first step is to home all the various components of the process chamber (the containers, the building plate and the recoater). While the recoater cannot move in the vertical direction, the building plate is moved along the Z direction to assure a condition of planarity. For this purpose, it possible to use feeler gauges. The distance between the recoater and the building plate is measured in different parts of the building plate, moving the recoater at different X values. The inclination of the building plate can be modified as well, thank to a slight rotation about the X axis, or about the Y axis.

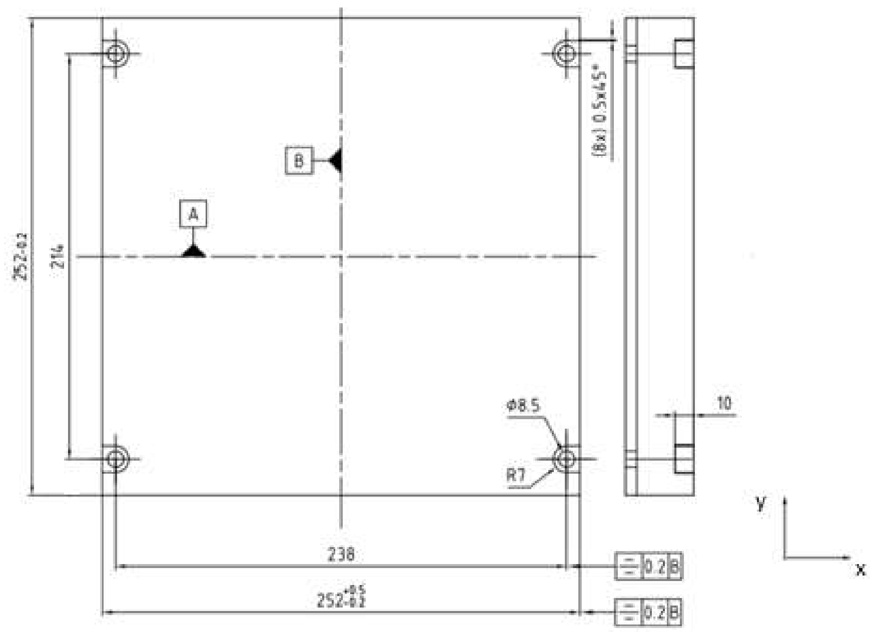


Figure 7-6: Technical drawing of the Steel building plate

A certain clearance between the plate and the recoater must be maintained, for the purpose of preventing interference.

Once the positioning of the building plate is considered satisfactory, the fresh powder container is then lifted in order to deposit the first layer. Measuring the thickness of the first layer is essentially impossible. Some practical observations can be made in this regard: the first layer should be clearly visible, but at the same time it should allow to glimpse the metal of the building plate.

When the part is high, a less thick first layer is preferred, thus promoting a better connection between the part and the building plate. The stresses due to the passing of the recoater may in fact be detrimental to the attachment of the part, if it is not properly secured to the plate.

From the very moment in which the door had been closed, it is suggested to start reducing the level of oxygen in the chamber. This process may take a long time and it generally slows down progressively as the percentage of oxygen goes down. The process won't start as long as this percentage is lower than 1.3%.

Once the laser is ready, the first exposure can be executed. This is a crucial passage of the printing, in which the laser beam melts not only the powder of the first layer, but also the building plate beneath, ensuring the connection between the part under construction and the plate. After the exposure (which may be carried out more than one time), the process can be launched.

Some ideas about the improvements

As stated before, the leveling procedure is still manual, although this is perhaps the most critical moment of the process. The thickness of the first stratum cannot be measured univocally, but only accepted or discarded on the basis of the experience of the user of the machine, and with the help of the feeler gauges. A large number of failures may happen because of a not properly deposited first layer. The scarce repeatability of the measuring instruments used in the levelling is definitely not helpful.

A computerized procedure would be certainly beneficial, because it would reduce the chances of a human error.

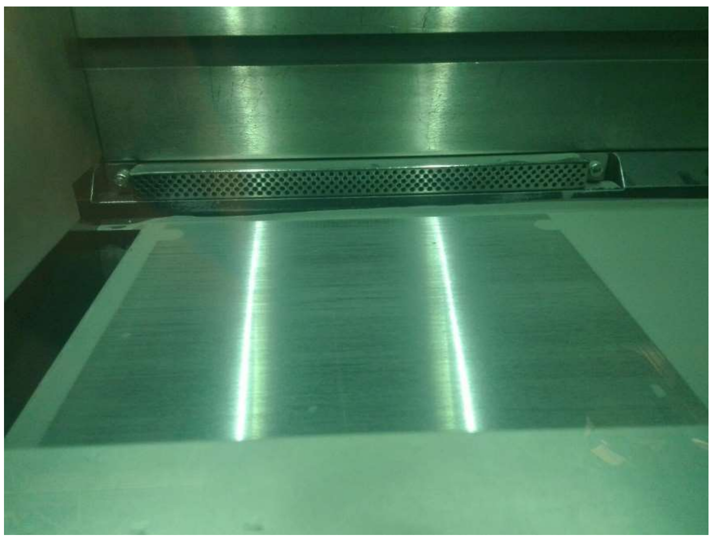


Figure 7-7: A photo of the first layer on the building plate, before than the first exposure is executed.

One of the most recurring issues in the printing is the collision between the recoater and the part under construction. Several justifications can be found for this, such as the bending of the part, which causes a little protrusion beyond the powder bed. When the recoater jams, the machine simply stops, because the collision may lead eventually to the breakage of the recoater and to a damage of the part.

As a matter of fact, long time before than the recoater jams, some vibrations can be actually noticed even touching the door of the machine. By simply adding on the recoater an accelerometer, which may be able to perceive some odd fluctuations, the issue may be corrected before than the collision occurs.

The easiest way to prevent the recoater from colliding would be to lower the building plate a bit more than the standard layer thickness, thus leading to a slightly thicker stratum (in the range of units of microns). Actually, the laser beam melts more than one layer at the same time.

This simple idea should be studied accurately, to define the optimized corrected thickness which should be used. A statistical approach should be used as well to detect a threshold above which the corrective maneuvers should be carried out. They should be actually implemented only when the presence of a possible collision is identified and indisputable, and not when a random unexpected acceleration occurs.
Based on the assumption that a laboratory should always be provided with an industrial scale for measuring the weight of the available powder, some scales should be included in the machine as well. In this way it would be possible to have an exact idea of the amount of powder located inside the machine, and thus preventing any mistake before than starting the process, without any need for moving it out of the machine.
Indeed, because of the fact that the dimensions of the various collectors and of the building plate are different, a full awareness of the powder loaded into the machine is not always possible.
Another simple device which should be added to the machine is a camera, which would allow the remote control of the printer. This kind of system is really common, even for low cost 3D plastic printers, but not yet for metal printers, maybe because of the temperatures reached or because of espionage risks.
A long time-wasting part of the build preparation is the powder filtering, which is executed through a vibrating system at times. It would be really useful if a recirculating system for the powder was installed on the machine, maybe using a solution to transport the particles. In this way the powder in the collector would be recycled while the machine is running, without the need to open the process chamber and so avoiding the dispersion of the inert atmosphere. A patent implementing such a system was already filed several years ago [37].

Report on the printing

Four printings of the part have been executed, only two of them being acceptable. As already stated before, when it comes to print larger parts, several complications which are not brought to light while printing little samples, simply emerge.
With regard to the first printing, the standard process parameters, suggested by the machine producer EOS, were selected as a starting point. And by the way, it must be pointed out that on not all of machines the process parameters can be controlled; on EOS machines for example, this possibility is acquired only with an optional “development kit”.

No preheating of the building plate has been initially executed. More than a single exposure has been carried out, in order to achieve a better connection between the part and the building plate. Indeed, since the part is quite high, the stress induced by the motion of the recoater, could even cause a detachment of the part under construction.
During the printing several interruptions occurred. The first one happened because of the shortage of powder in the reservoir. As already stated previously, the overfeeding parameter was set to 300%, therefore a three times bigger amount of powder was actually necessary to complete the printing. As a result of this too conservative value, the process chamber needed to be opened, with the purpose of adding more powder. The inert atmosphere inside the chamber was of course dispersed, and a result a really clear line is visible on the part.
The recoater jammed several times with the part throughout the printing. Several reasons may be detected to this issue.
Most probably the high energy density played a major role in those interferences, especially when the complex curvature of some portions led to an excessive energy concentration. In the Figure 7-8 it is possible to observe some overheating of the metal powder, in the proximity of the contours, which manifests with darker or even bluish regions. However, the overheating portion is not particularly serious in the moment captured in the photo, compared to what could be seen at other times of the printing. The low quality of the image stems from the fact that the picture was taken from the outside of the machine, while it was running.

Figure 7-8: A moment of the first printing.

Some soot can be seen in the support region as well. Moreover, although in the image it is not visible, some "balling" was present too in those problematic areas: in some moments of the printing there was an actual depression between the overheated contour and the core.
As a result, the recoater kept smashing against the part exactly on those critical regions.
On the top of that, the EOS software crashed, most likely because of problems in the upgrades of the drivers.

Figure 7-9: A photo of the first printed part with the failure of the supports.

The part was completed anyway, after a reduction of the energy parameters.

Various precautions were taken for the second printing: the building plate was preheated up to 200˚C (which was the maximum selectable value), the position of the part was modified, the overfeeding parameter was reduced to 120%, some supports were removed from self-supporting features and the energy of the laser was lowered.

Figure 7-10: Photo of the failed second printing plate. Some other coupons were added in the same process.

The second printing failed after a few hours of printing, because some of the supports were basically chopped-off by the recoater and because a new intersection occurred. Although more than a single exposure was executed on the first layer, the connection of the part onto the plate was maybe not perfect.

A possible explanation for this inconvenience may be a not proper thickness of the first layer, but this wouldn't explain why the other coupons on the same building plate were printed without problems, except for one. As a matter of fact, the second coupon (a key chain) in the upper right failed during the printing, and it was positioned on the same horizontal line of the spot from which the supports of the bracket were ripped off.

Actually, some dirt was perceptible on the blade of the recoater in that location, but it was easily removed.

Another possible explanation may be an imprecision in the grinding of the build plate, since it was not a new one, but it was re-machined after the first-time use.

The value of temperature equal to 200˚C was chosen because it is reported in many papers, and because it was the highest available on the machine. One of the disadvantages of using the preheating of the build plate is that it is necessary to wait a certain period of time before than the process chamber can even be opened, and some time must be waited as well before than starting to manipulate the parts. This for sure slows down the entire process, especially when another process should be started immediately after.

It is certainly true that the effectiveness of the preheating weakens as the part grows, but some benefits can be pointed out anyway, especially when the material is particularly brittle.

The energy values were modified carefully, using this well documented formula, which relates four fundamental quantities of Selective Laser Melting:

$$E = \frac{P}{v \cdot h \cdot t}$$

P represents the laser power, v is the scanning speed, t is the thickness of each layer, h is the hatch spacing, while E is the energy density [J/mm^3].

Once it was established that no change would have been applied to the scanning speed, to the hatch spacing and to the thickness, the only alterable parameter was the laser power.

The default value set on the machine was equal to 285 W and this led to the following calculation:

$$E = \frac{285}{960 \cdot 0.11 \cdot 0.040} = 67.47\ J/mm^3$$

This value of the energy density is actually in the middle of the suggested range, which varies approximately from 50 to 80 J/mm^3 for Maraging Steel.

For the second printing the energy density was lowered to 60 J/mm^3- and in any case way higher than the lower limit- and the laser power was computed consequently:

$$E = 60\frac{J}{mm^2} \rightarrow P = E \cdot v \cdot h \cdot t = 253\ \mathrm{W}$$

This value of the laser power was used also for the following printings.

Although approaching to the lower limit of the energy density would have maybe guaranteed a “safer” printing, in terms of the risk of overheating and of collision, excessively low values of energy may be catastrophic when dealing with fully functional parts.

Some voids may occur, and the density of the final component might fall below the expected one.

Conventional wisdom says that the parts showed by the machine producers sometimes don’t meet these requirements but focus more on the visual appearance of the coupon, rather than on the functionality of component, because the chosen energy is lowered to avoid the abovementioned issues. This is of course a statement which is not at all supported by official sources or certified in any way.

However, not functional parts may be used for example as prototypes for fitment checking, having the advantage of being built in the same material of the final component and with a comparable weight. Rapid Prototyping was the former name of Additive Manufacturing, after all.

Another problem related with the second printing is that although the energy related to the core was reduced, the energy associated to the contouring remained unchanged. Decreasing this last parameter proportionally to the abatement of the energy of the core would have been maybe a reasonable choice.

Figure 7-11: The printed bracket on the building plate.

With regards to the third printing, the biggest difference with the previous one was the complete removal of the contouring. This led to an unequivocally lower surface finish, but it allowed to complete the printing without any interruption, or different kinds of problems.

The process parameters (the energy density in particular, and the temperature of the building plate) were exactly the same as the second printing.

As a result of the changings in the contouring, the processing time, originally equal to about 30 hours, was reduced consequently to about 26 hours.

Figure 7-12: The cleaning process after the building.

Chapter 8
Cost considerations

When it comes to estimate the costs for Additive Manufacturing parts, generally it is not easy to obtain precise values, especially for variable costs. Indeed, there are still many aspects which must be standardized or optimized. Even if in some cases the dealers of the machine provide some indications, sometimes the used values must differ for practical reasons from the suggested ones.

One of the most glaring examples of the manufacturers' discretion is related to the build plate. Some of them prefer to purchase the build plate from the authorized dealer only, instead of machining it *intra moenia*, because of the very close required tolerance of flatness. Except for these requisites, the build plate has a very simple geometry: it is basically a piece of metal in the shape of a parallelepiped, with some screwed holes for the clamping to the machine. On the contrary, other manufacturers normally produce the build plate by themselves, with conspicuous economic benefits. It should be noted that after the first building, the plate should be milled and grinded in any way by the user.

Continuing the example, it is also difficult to compute accurately the number of parts which can be printed with a single plate, machined over and over. First of all, it must be pointed out that there is a minimum thickness of the plate, below which it should be replaced, because of the changes in heat transmission. Furthermore, it is not well defined a suggested depth of cut for the grinding and the milling and there is no standardization.

Another consideration is that the SLM market is rapidly growing. This means that, especially for accessories and for powders, the average market price is currently decreasing in some situations. Yet, it must be taken into account that some machine producers may issue a veto on the possibility of using components from different companies, withdrawing the warranty.

It goes without saying that if bigger quantities of these accessories are acquired, a lower price could be negotiated.

The possibility of controlling the process parameters on the machine is a really interesting topic as well. As mentioned before, this authorization can be obtained generally only if special licenses are purchased, such as the EOS "Developer kit". Without this permit, the processing parameters are simply invisible to the operator, who cannot modify them and therefore make any mistakes. This kind of press-and-go machines can be perfectly suitable if non-critical parts are intended to be printed, or if the machine producer is also the only powder supplier, or if a post-treatment is anyway included in the work flow (a certain freedom in the parameters should be permitted to optimize the surface finish of the printed parts).

On the other hand, if there is the willingness to buy the powder from a different supplier, or to experiment (for example with MMCs), the Developer kit will be indispensable. The same applies to research groups which want to embark on detailed investigations of the physical mechanisms governing the process, or to companies which want to develop their own parameters.

In this case, although EOS is tending to offer more flexibility in the most recent models, the cost of this extended license should be added to the general budget.

Similar remarks may be made about the authorization to print some materials with the same machine, even in cases where the safety requirements are respected. Indeed, some processing parameters may be locked out, because one more license must be acquired.

Among the accessories for the process it must be included an industrial vacuum cleaner for the machine cleaning and a sieve. This one should be very closely woven, in order to filter accurately the burnt and then scattered powder particles from the previous printing process. The filtered powder can be generally put again in the feeding system of the machine. Different types of sieves are sold, having various dimensions, depending on the processed material.

The timing related to the preprocessing for the machine preparation and the cleaning of the process chamber may obviously vary with the operator’s skill level, but not significantly with the complexity of the parts. Of course, a multifaceted part may take more time than one with a basic geometry to be cleaned, or it may even require a vibrating system for the removal of the powder (especially for parts with cavities). Besides, although it is recommended to maintain a high level of cleanliness of the machine, the procedure will be less accurate if the material won’t be changed in the next printing.

For this reason and in order to prevent any form of contamination between different powders, some companies prefer to restrict the use of every machine to a single material in their production plants (different steel powders can be used on the same machine, though).

Specific procedures should be followed for the storage of some materials: sometimes, to avoid chemical reactions and degradation, protection from humidity and from light must be provided.

The possibility of recycling the powder is still an outstanding question. In the traditional manufacturing the percentage of recycled material is generally low, in order to maintain a stable level of quality of the produced components. For instance, in the injection molding process a part can be considered as built with virgin material, as long as the recycled re-grinded material from the discarded parts is not higher than the 20%.

Talking about SLM, only a short amount of the powder laid down in a building process has been actually added to the component. The most part of it has just been deposited on the plate by the recoater, but it did not undergo perceptible modifications. The main reason why recycling is such an important issue for this AM technique is obviously that the powder can be really costly, and every waste should be carefully prevented.

When it comes to studying the effects of recycling, it is necessary to consider the chemical modifications of the powder, and in particular the creation of nitrides and oxides, and the variations in the "flowability". This is a very important property of the powder, which guarantees a homogeneous distribution on the building plate. It is affected by the morphology of the powder and by the distribution of the particle size.

Renishaw studied systematically the problem, using maybe the most expensive and reactive material among those available for Additive Manufacturing, the Ti6Al4V alloy [38]. In this test after each building, the remaining powder was sieved and placed again in the feeding system, without any addition of virgin powder. The procedure has been repeated 38 times, until there was not enough powder left for a complete build. At this stage the morphology of the powder particles has been studied with a Scanning Electron Microscope (SEM). The results show that the shape of the particles did not change, but the smaller one disappeared progressively and the average dimension slightly increased. This is due to the fact that probably the small particles were sintered together, forming oversized agglomerates which were rejected during the sieving.

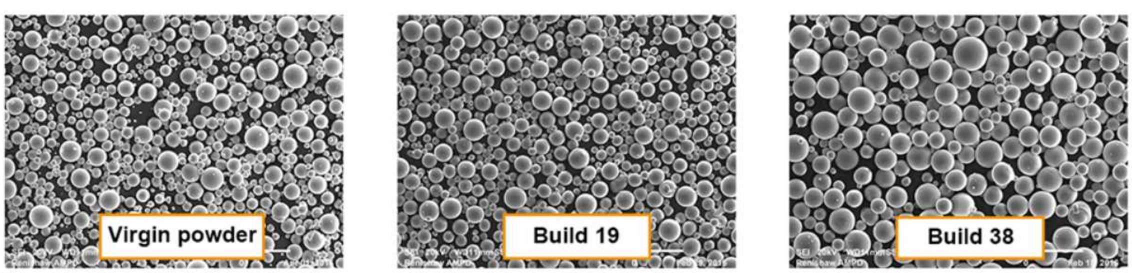


Figure 8-1: The evolution of the particle size of cyclically recycled powder. Reprinted from [39].

Talking about the percentage of oxides and nitrides, it can be observed a continuous but only little increase. This is achieved also because of the controlled inert atmosphere in the process chamber and during the sieving.

To sum up, according to Renishaw, recycling the powder caused almost insignificant variations of the chemical and morphological aspects of the particles, but it led at the same time to a better flowability.
The Ultimate Tensile Strength (UTS) became even larger in the few last builds, because of the interstitial oxygen and nitrogen.

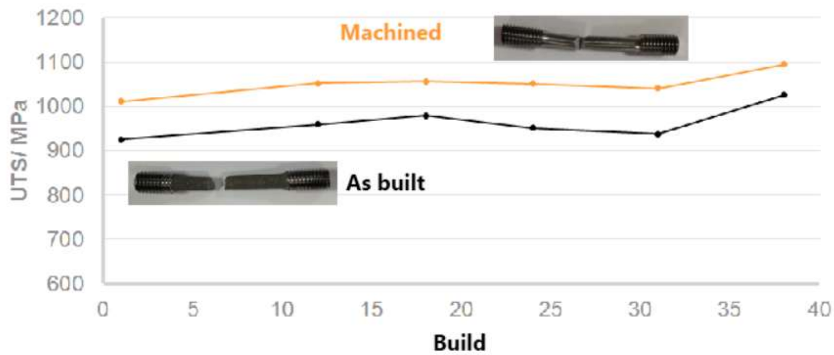


Figure 8-2: General trend of the Ultimate Tensile Strength, varying with recycling. Reprinted from [39].

This example, published by Renishaw, must be considered as “extreme”, because of the fact that the powder has never been mixed with some virgin powder, as it normally happens in the laboratories. Furthermore, although the results of this tests are encouraging, they cannot be considered valid also for other materials, such as aluminum or steel. Attention should be paid also to the equipment used to create the inert atmosphere, which can vary from machine to machine and to producer to producer.
Still on this subject, the cost of producing an inert atmosphere shouldn’t be forgotten. Metals such as Maraging Steel need a Nitrogen atmosphere, whereas to print Aluminum or Titanium, Argon is recommended.
It must be remembered also that the safety standards may be different, in relation to the material. For this reason, a laboratory in which Steel is printed, may be not in accordance with the regulations for Aluminum.
The costs of the safety equipment, albeit moderate, should be added as well to the budget. They include plastic gloves, masks and disposable lab coats for quick and not risky operations, but also a hermetic ventilator with an included mask, a jumpsuit and protective gloves for high temperatures, when some harmful to health procedures are executed.
A growing literature is trying to build some models to predict the costs of AM for metals.

Conclusions

The foregoing discussion has attempted to analyze all the steps which led to the complete redesign of a mechanical component for Additive Manufacturing.

It is well known that this outstanding technology enables the fabrication of parts, simply by adding consecutive layers of material and essentially without any limitation in the geometry. Although nowadays Additive Manufacturing (AM) entered everyone's life, also due to the recent expiration of some patents, its industrial implementation is still limited to only a few applications.

This thesis project, which was developed in cooperation between Politecnico di Torino, Fiat Chrysler Automobiles and McMaster University in Hamilton (Canada), can be placed exactly in this context. Indeed, several companies are currently interested in understanding the real power of Additive Manufacturing, together with its economic justification and its limitations.

Selective Laser Melting (SLM) and the other technologies which employ metallic powders are increasingly drawing the attention, because of their vast potential in several fields, such as the automobile and the aerospace sectors, but also the biomedical one.

The part under consideration is a hot-end bracket, originally made of Cast Iron and weighing 2.1 kg. The objective set was to print a functional mechanical component, having equal performance and reliability of the existing one, but also lighter than that. The essential instrument, necessary to accomplish this task, was Topology Optimization.

Although this mathematical method was a subject of study for a long time, it eventually gained feasibility thank to Additive Manufacturing, by virtue of the overcoming of manufacturability limitations, which are now permitted by this technology.

The first item on the agenda was the construction of a model of the actual part, including a modal analysis, a thermal-structural analysis and a frequency-response analysis. A complete awareness of the functioning of the current bracket was an obligatory step for the validation of the results originating from Topology Optimization. Careful attention was therefore devoted to the calibration of the model, which was built using the engineering simulation software Ansys.

The optimization of the part was carried out on the software SolidThinking Inspire and it has led to a 40% weight reduction.

Numerous problems were encountered in the management of the modifications of complex STL files, and above all in their preparation for the validation. For this purpose, the indistinct and rudimentary shapes obtained with Inspire, have undergone a long cleaning process. Some smoothening algorithms were tried and then selected, in order to procure a file ready to be loaded on the machine.

During the period of study in Canada, the simulations were flanked by a study of various theoretical aspects of the present case: the current state of the art of the exhaust system, the latest progress in Selective Laser Melting, the mathematics behind Topology Optimization, the smoothening algorithms, et cetera.

A long period of time was dedicated to the printing process. After the determination of the best positioning of the part on the building plate, several printings were performed on the EOS M 280 machine, available in the laboratories of McMaster University. After some failures and some adjustments of the suggested process parameters, the fabrication of the part was completed without any interruption.

In conclusion, it is possible to affirm that day after day Additive Manufacturing for metals is getting closer to a well-established industrial employment in many areas. The road ahead is still a long one, but inspiring and stimulating, at the same time.

The development of the technology is undoubtedly slowed down by the high costs of the powder and of the machine. The not yet profound comprehension of the physical phenomena which regulate the printing process and the extremely high number of variables involved, make it necessary a still too empirical calibration of the process parameters.

Although the machine producers share their data with their users, generally those are not specifically selected for a precise application. For this reason, some tests prior to the actual printing are fundamental prerequisites.

The production of large complicated parts is often impeded by the limitations on the dimensions of the process chambers, but also by the not widespread know-how in dealing with this kind of parts.

Resorting to the process simulation could be a solution to some of these issues, despite the fact that this field is not yet completely evolved.

A fundamental boost in the future fine-tuning of AM is standardization, which is already actively working. A standardized quality control procedure would be extremely time-saving, compared to the complete range of tests which are nowadays performed on every printed part.

As has happened for the 3MF Consortium, joining the forces of various companies could be an interesting resolution for the advancement of this extraordinary technology.

Bibliography

[1] B.A.A.L. van Setten M. Makkee, J.A. Moulijn, *Science and technology of catalytic diesel particulate filters,* Catalysis Review, (2001), pp. 489-564

[2] A.C. Serrenho, J.B. Norman, J.M. Allwood, *The impact of reducing car weight on global emissions: the future fleet in Great Britain*, Philos Trans A Math Phys Eng Sci, (2017)

[3] *Riduzione del consumo di carburante: misure operative*, UFAC Whitepaper, (2015)

[4] R. Modaresi, S. Pauliuk, A.N. Løvik, D.B. Müller, *Global Carbon Benefits of Material Substitution in Passenger Cars until 2050 and the Impact on the Steel and Aluminum Industries*, Environ. Sci. Technol, (2014), pp. 10776–10784

[5] S. Wenlong, C. Xiaokai, W. Lu, *Analysis of Energy Saving and Emission Reduction of Vehicles Using Light Weight Materials*, Energia Procedia, (2016), pp. 889-893

[6] ISO/ASTM DIS 52910.2, "*Guidelines for design for additive manufacturing*", (2016)17

[7] I. Gibson, D. W. Rosen, B. Stucker, *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, Springer, (2009)

[8] M. Hall, M. Kristofik, *Conformal Cooling*, Rochester Institute of Technology Whitepaper, (2015)

[9] S. Mayer, *Optimised mould temperature control procedure using DMLS*, EOS Whitepaper, (2005)

[10] *EOSINT M 280- Training manual,* (2010)

[11] J.P. Kruth, P. Mercelis, J. Van Vaerenbergh, *Binding mechanisms in selective laser sintering and selective laser melting,* (2005), pp. 26-36

[12] M. Yakout, A. Cadamuro, M.A. Elbestawi, S.C. Veldhuis, *The selection of process parameters in additive manufacturing for aerospace alloys*, Int J Adv Manuf Technol, (2017)

[13] US Patent 6,423,926 B1, *Direct-metal-deposition (DMD) nozzle fault detection using temperature measurements*, (2000)

[14] M. Soodi, *Laser Cladding compared with TIG welding to repair and refurbish railway axles,* CORE 2010, Conference on Railway Engineering, Wellington, New Zealand, (2010)

[15] J.B. Jones, P. McNutt, R. Tosi, C. Perry, D.I. Wimpenny, *Remanufacture of turbine blades by laser cladding, machining and in-process scanning in a single machine,* 23rd Annual International Solid Freeform Fabrication Symposium, Austin, Texas, (2012), pp. 821-827

[16] J. Hiemenz, *Electron Beam Melting,* Advanced materials and Processes, (2007), pp. 45-46

[17] S. Tammas-Williams, P.J. Withers, I. Todd, P.B. Prangnell, *The Effectiveness of Hot Isostatic Pressing for Closing Porosity in Titanium Parts Manufactured by Selective*

Electron Beam Melting, Metallurgical and Materials Transactions A, (2016), pp. 1939-1946

[18] H. Hassanin, E. Khamis, Q. Chunlei, N.J.E. Adkins, *Net-shape manufacturing using hybrid selective laser melting/hot isostatic pressing,* Rapid Prototyping Journal, (2017), pp. 720-726

[19] M. Thöne, S. Leuders, A. Riemer, T. Tröster, H.A. Richard, *Influence of heat-treatment on Selective Laser Melting products – e.g.,* 23rd Annual International Solid Freeform Fabrication Symposium, Austin, Texas, (2012)

[20] A.Fortunato, A. Lulaj, S. Melkote, E. Liverani, A. Ascari, D. Umbrello, *Milling of maraging steel components produced by selective laser melting,* The International Journal of Advanced Manufacturing Technology, (2018), pp. 1895-1902

[21] A. Wiesner, D. Schwarze, *Multi-Laser Selective Laser Melting,* 8th International Conference on Photonic Technologies LANE, (2014)

[22] T. Heeling, L. Zimmermann, K. Wegener, *Multi-Beam Strategies for the Optimization of the Selective Laser Melting Process,* 27th Annual International Solid Freeform Fabrication Symposium, Austin, Texas, (2016), pp. 1428-1438

[23] Y. Chivel, *New approach to multi-material processing in selective laser melting ,* 9th International Conference on Photonic Technologies LANE, (2016), pp. 891-898

[24] R. Vrana, D. Palousek, D. Koutny, P. Krejci, *Impact resistance of lattice structure made by Selective Laser Melting technology,* MM Science Journal, (2015)

[25] R.K. Bhatnagar, G. Gupta, *A review on weldability of cast iron,* International Journal of Scientific & Engineering Research, (2016), pp. 126-131

[26] M. Hatate, T. Shiota, N.Abe, T. Tanaka, *Bonding characteristics of spheroidal graphite cast iron and mild steel using electron beam welding process,* Vacuum, (2004), p. 667-671

[27] B.J. Thomas, A. Sutton, M.C. Leu, N. Doiphode, *Bonding of 304L Stainless Steel to Cast Iron by Selective Laser Melting,* 2017 Annual International Solid Freeform Fabrication Symposium, (2017)

[28] W. Sha, Z. Guo, *Maraging steels: Modelling of microstructure, properties and applications,* (2009)

[29] O. Sigmund, K. Maute, *Topology optimization approaches: A comparative review,* Structural and Multidisciplinary Optimization , (2013)

[30] C. Razvan, *Overview of structural topology optimization methods for plane and solid structures,* (2014)

[31] M. Zhou, N. Pagaldipti, H.L. Thomas, Y.K. Shyy, *An integrated approach to topology, sizing, and shape optimization,* Structural and Multidisciplinary Optimization, (2004), pp. 308-317

[32] M. Zhou, Y.K. Shyy, H.L. Thomas, *Checkerboard and minimum member size control in topology optimization,* Structural and Multidisciplinary Optimization, (2001), pp. 152-158

[33] J.D. Hiller, H. Lipson, *STL 2.0: A proposal for a universal multi-material Additive Manufacturing File format,* (2009)

[34] ISO/ASTM 52915 – 16, *Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2,* (2016)

[35] J. Vollmer, R. Mencl, H. Müller, *Improved Laplacian Smoothing of Noisy Surface Meshes,* (2001)

[36] M. Brettel, N. Friederichsen, M. Keller, M. Rosenberg, *How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective,* (2014)

[37] J.A. Turner, Sudarsanam Suresh Babu, Craig Blue, *Advanced Simulation for Additive Manufacturing: Meeting Challenges Through Collaboration,* Workshop Report for the Advanced Manufacturing Office, U.S. DOE Office of Energy Efficiency & Renewable Energy, (2015)

[38] US Patent 7,887,316 B2, *Selective Laser Sintering powder recycle system*, (2009)

[39] L. Grainger, *How much can you recycle metal additive manufacturing powder?,* Renishaw, (2016)

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