Politecnico di Torino
Master's Degree in Mechanical Engineering

Design for additive manufacturing: distortions correction and build improvements

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Avio Aero

A GE Aviation Business

The present Master Thesis Project has been developed in collaboration with Avio Aero who has approved the content of this document. Avio Aero is *"a GE Aviation business which designs, manufactures and maintains components and systems for civil and military aviation"* [1]. Among different plants across Italy, Poland and Czech Republic, the company's headquarter and largest production facility is located in Rivalta di Torino (TO), while in Cameri (NO) in 2013 was inaugurated one of the largest factories in the world entirely dedicated to Additive Manufacturing. In 2017 Avio Aero, in collaboration with Polytechnic of Turin, created the Turin Additive Laboratory (TAL), or *"a joint lab created to collaborate on strategic research topics for the aviation industry, such as identifying new materials for this production technology"* [1].

“Datemi un punto d’appoggio e solleverò il mondo!”

Cit. Galileo Galilei

Table of Contents

Abstract

In recent decades, various industrial revolutions have changed the domains of manufacturing in many aspects. In the last revolution, namely Industry 4.0, a new type of manufacturing process has taken place, the Additive Manufacturing. Additive manufacturing process has undergone great progress in the past few years and it’s going to revolution the manufacturing industry. Powder Bed Fusion technologies are the most developed Additive Manufacturing technics for metal material. Even this fact, there are still some limits.

The aim of this master thesis is to deeply study, develop and apply the compensation procedure. This one is a pragmatic solution to avoid, at least to reduce, the distortions and geometrical defects of components produced with Powder Bed Fusion technologies. At the first time, each typology of compensation will be studied and will be descripted all advantages and disadvantages. It will continue with the application of compensation procedure to two cases of studies: Canonical Model and Power Gear Box.

The master thesis work has been developed in collaboration with Polytechnic University of Turing and GE Avio Aero

Chapter 1

Additive Manufacturing

1.1 History and Development

The development and diffusion of Additive Manufacturing (AM) technologies is quiet recent respect the classical manufacturing technologies. [2]
In the 1980s the first 3D printer was developing and in 1984 Chuck Hull received his own patent for the printer which he created. It was a stereolithography printer which used a photosensitive polymer selectively cured by means of an UV laser layer-by-layer. For the power bed sintering system, we must wait until 1992 when was commercialized the first SLS (Selective Laser Sintering) machine. During '80s and '90s Rapid Casting and Rapid Tooling take parts: cores for foundries and inserts for molds were easily realized in a faster way by AM technologies. Tools are still produced by AM machines.

Figure 1, mold with sand cores 3d printed [3]

The first LAM (Laser Additive Manufacturing) system for titanium alloy was developed in 1997 by AeroMet. In the 2006 Stratasys installed the first Electron Beam Melting (EBM) machine in the USA. During the first decade of 2000s AM technologies were mostly used for Rapid Prototyping but the innovations and the development of the associated technologies to AM have led to combine Rapid Prototyping with Rapid Manufacturing, as shown in Figure 2 [4]. This allowed the fabrication of end-usable objects and today 3D printing is called Additive Manufacturing.

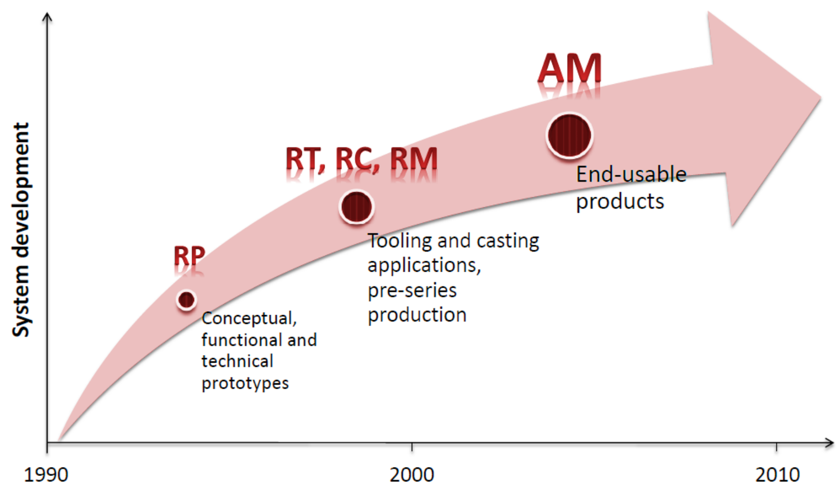


Figure 2, functionality of AM during its evolution [5]

1.2 Application of Additive Manufacturing

Nowadays exists many AM technologies. Many materials can be processed: polymers and metals, too. These characteristics, combined with the multiple advantages of AM, make various application possible.

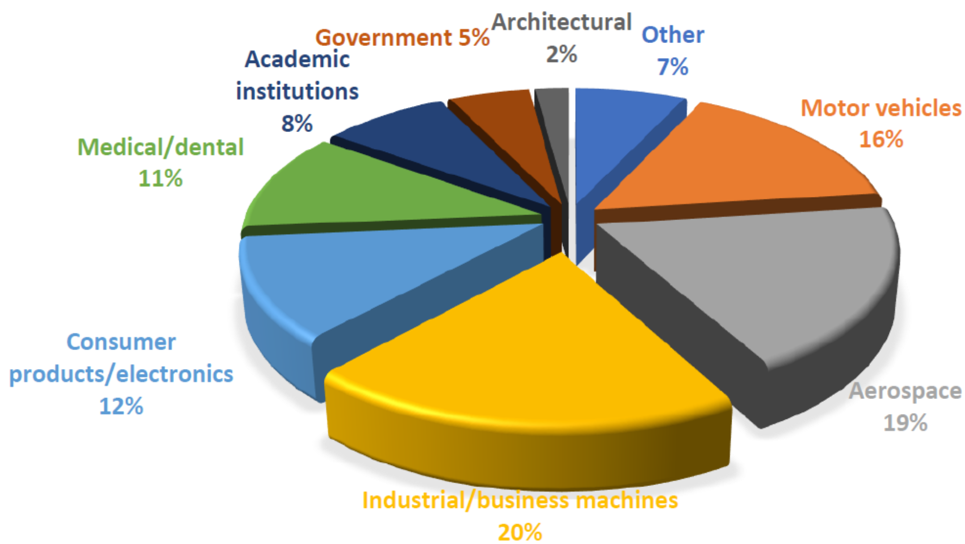


Figure 3, Percentage of Industrial and Public Sectors using AM technologies [6]

As shown in Figure 3, the sectors with AM application are many. The biggest part is taken by Aerospace and Automotive industries. Prototypes, pre-series, tools are produced with less time, using less material thanks to AM technologies; definitive components are produced, too. Aerospace industries need to work with components in nickel, titanium, high strength steels alloys and AM makes possible to reduce weight respect conventional manufacturing process, which are expensive and time consuming. In automotive AM is used to produce polymeric parts for intern, too. [7]

Figure 4, car's wheel bearing support [8]

In medical and dental sectors AM makes possible to produce Titanium alloy prosthesis. [9] The osseointegration of titanium alloy and free geometry of AM makes possible to realize custom orthopedic prostheses, biological chips. [10]

Figure 5, medical application [11]

With 3D printing, jewelry designers are able to produce designs that would be incredibly difficult to hand carve in the traditional manner. Thanks to a precisely controlled laser, extraordinary design details—delicate filigrees, raised text, and detailed pavé stone settings—can be captured with amazing sharpness. [12]

Figure 6, 3d printed and relative casting pieces [12]

1.3 Advantages and limits

AM is changing the way to design components; is changing the process chain. These changes are due to the advantages of this technologies.

- Freedom of design: this is probably the most important characteristic of AM technologies. Until the parts are processed layer by layer, the geometry realizable has less limits respect traditional technologies. It is possible to realize organic shapes, internal holes, intermediate density. In this way the components are lighter: no more in influent material is used [13] [14].
- Parts customization: now it is possible to realize one-piece-assembly. Many components can be integrated, in this way it is possible to reduce part numbers and the assembly operations [15].
- Lead time: components can be directly produced from CAD files trough few informatic process. This decreases the lead time respect traditional technologies, which needs molds or to start from massive raw blocks.
- Less waste: AM produce less waste material respect subtractive manufacturing, as shown in Figure 7, and AM product can be lighter.

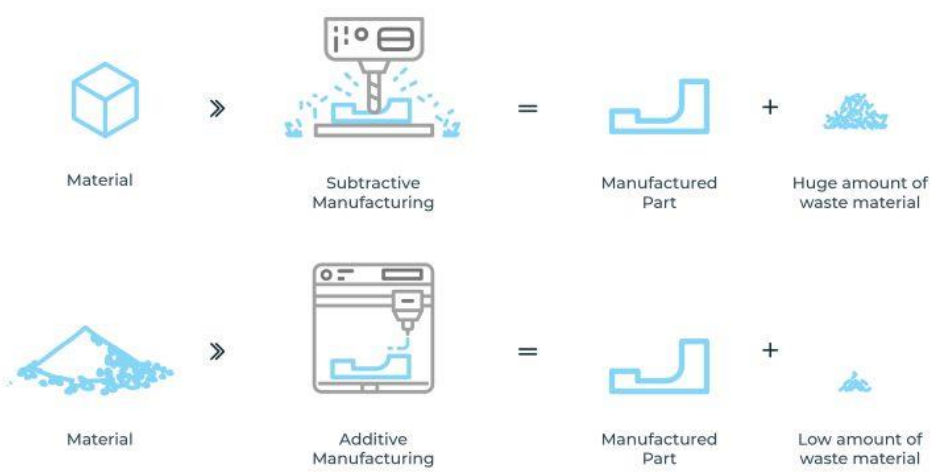


Figure 7, scheme of subtractive manufacturing and additive manufacturing [16]

- Material processable: AM technologies is characterized by the infinitesimal melting-solidification interval. This makes possible to process new material, scalmalloy is an example.
- Cost: less material used, less lead time and freedom of design makes AM technologies cost competitive respect traditional technologies. As shown in Figure 8, traditional technologies cost production is strongly dependent of complexity of components, but this is not equal for AM.

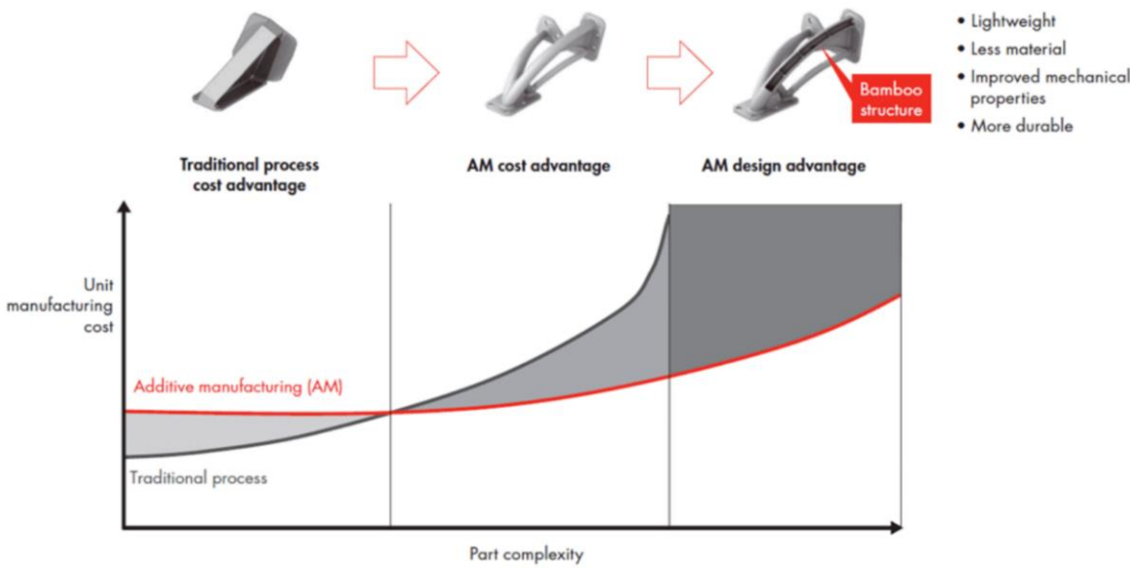


Figure 8, convenience of AM in function of part complexity [5]

On the other hand, AM technologies still have some limits:

- Maximum volume of components: powder bed technologies present a limit volume processable. Other technologies have bigger volumes, SLA and DED for example.
- Initial Investment: machines are so expensive, machine for metals in particular. The raw materials are more expensive respect the similar for traditional technologies. On the other hand, it is true too that the material used is less. [17]

- Large volume production: until AM machines have limit volume, the production of large volume requires long time.
- Post-processing: surface finish and dimensional accuracy are limited so additional manufacturing process could be required.
- Defects: layering and multiple interfaces can cause defects in the product.

These features make additive processes the most promising ones among emerging technologies, thanks to their capabilities of producing complex shapes and making free from constraints proper of conventional methods of manufacturing [18] [19]

1.4 Additive Manufacturing technologies

"The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [20] this is the definition of AM given by the American Society of Testing and Materials (ASTM). In according to the ISO/ASTM52900-15 standard of AM process categorization, there are seven different types of processes that an AM system might implement to 3D print [21], Figure 9:

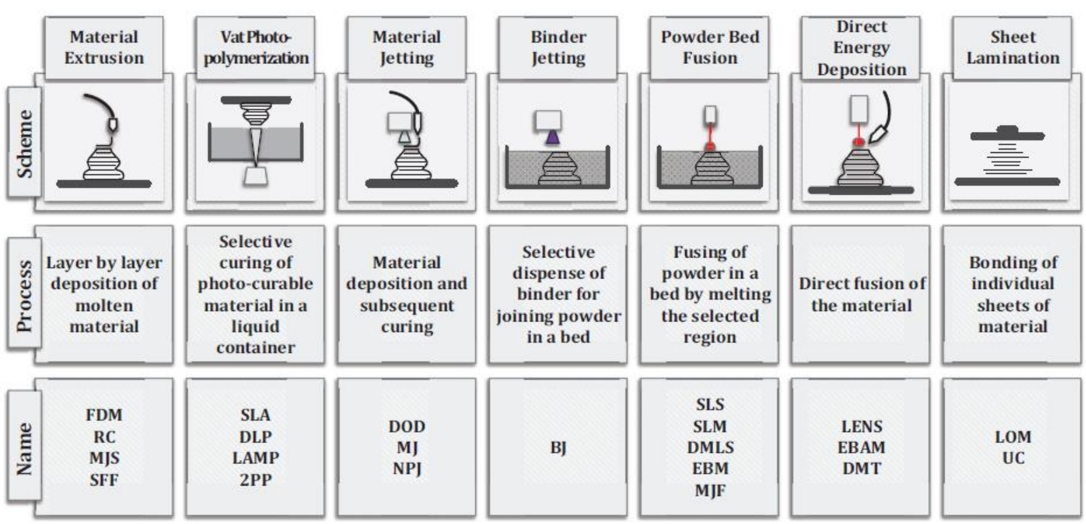


Figure 9, additive manufacturing processes

- Material extrusion: A thermoplastic material is deposited from an extruder onto a substrate. A plastic filament is melted by a heating mechanism and extruded through a hot end. Moreover, the same process can be used with viscous materials such as, organic tissue, clay, concrete or even food.
- Vat photopolymerization: this technology uses a vat of liquid photopolymer resin which is exposed to an energy source, like a laser beam or digital light projector, so the material hardens layer-by-layer.
- Material jetting: piezoelectric printheads, spray a liquid material onto a substrate. Material is a photopolymer, which is becomes hard with an ultraviolet light.
- Binder jetting: A process by which a liquid bonding agent is deposited onto a bed of powder. Can be used with metal, gypsum, glass, sand, and several others.
- Powder bed fusion: The process feature is that an energy source, melt a bed of powder to aggregate the individual particles. The energy source may be a laser or electron beam. Generally, this technology is associated with metals such as Inconel or titanium, as well as plastics such as PEEK.
- Direct Energy Deposition: Metal powder or wire feedstock, feeds a nozzle which is in front of an energy source, like a laser or electron beam, mounted on a multi axis robotic arm. The material is melted onto a substrate layer-by-layer.
- Sheet Lamination: In this process, sheets of material are fused together, with the desired shape etched into each shape. The final object is then removed from the block of bound sheets. This technology is currently most not only often used with paper, but also with metal and plastics. [3]

Let’s focus on the most common technologies.

1.4.1 FDM

FDM is the acronym of Fused Deposition Material. It's a technology characterized by the use of a heating chamber to liquefy a polymeric filament. This one is pushed into the chamber by a tractor wheel arrangement and this pushing generates the extrusion pressure. Materials used in this process are polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polyphenylsulfone (PPSF), PC-ABS blends, and polylactic acid (PLA). The machines and the materials used are not so much expensive. Probably, it is the most cost-effective processes. The disadvantage is the low resolution on the z-axis; lower resolution respect the other axis and respect the other AM technologies. This also mean that for components requiring a high grade of surface finishing, sometimes further operations are required that can take a lot of time. Supports are required but can be realized with different material respect the component. It is possible to realize not-fully dense component, in this way the time and weight decrease.

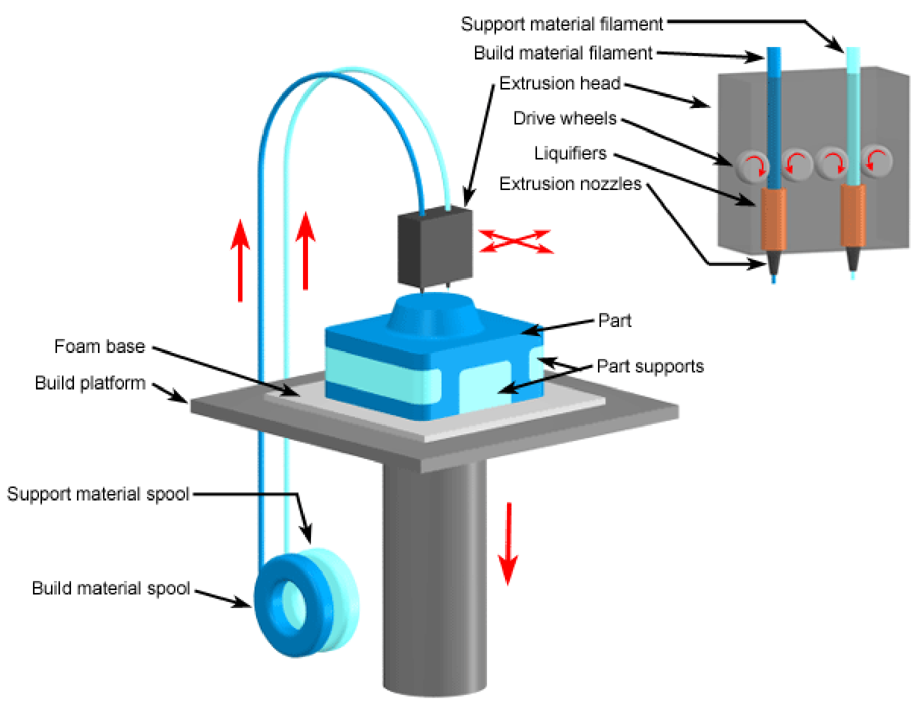


Figure 10, FDM scheme [22]

It is useful to summaries advantages and disadvantages with the following list.

- Advantages:
    - End-user thermoplastic processable
    - Possibility to realize support with soluble materials
    - High dimension accuracy
    - Lower machine cost respect the other AM technologies.
- Disadvantages
    - Supports are required
    - Impossibility to use the total of volume

1.4.2 SLA

SLA is the acronym of stereolithography, and it can be considered the first proper process of additive manufacturing. It is the process of curing a liquid polymer that is photosensitive to UV sources, to which it reacts by establishing chemical bonds, and becomes solid. Each layer is realized by photopolymerization of the liquid polymer between the build platform and the free surface of the vat in which it is submerged. In this passage, the ultraviolet laser scans specific trajectories of the layer, to draw the contour of the current section, plus internal passages according to hatching strategy. Once the polymerization is completed, the build plate is lowered in order to refill the next layer of polymeric resin to be cured, repeatedly until the part is completed.

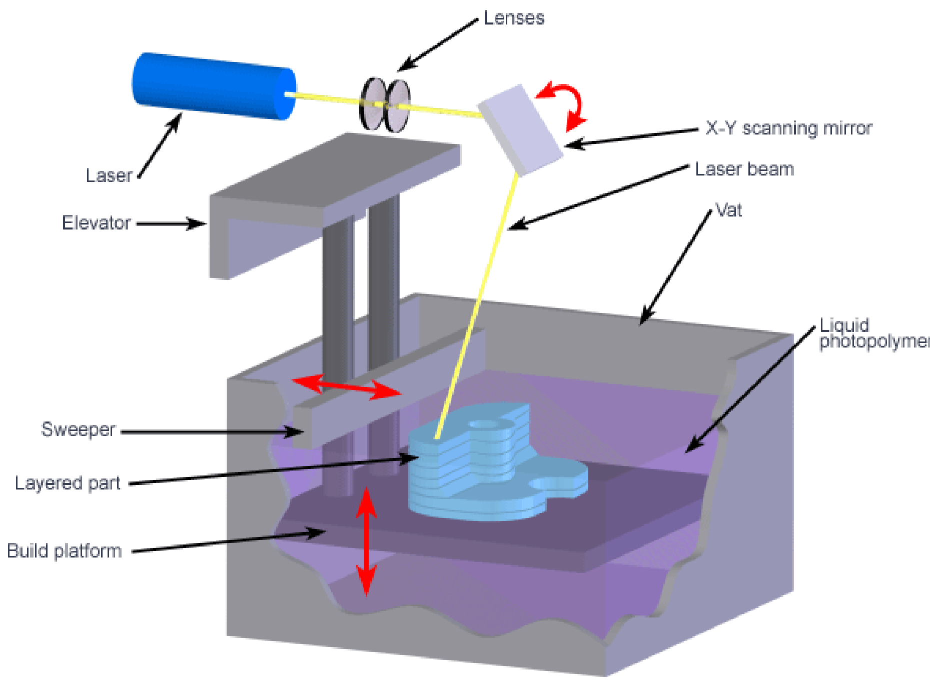


Figure 11 - Schematic representation of stereolithography machine. [22]

This technology is slower respect the other polymeric AM technologies, and the polymerization causes consistent deformation. The material most commercially used resin for SLA machines is epoxydic-based with acrylate addition.

It is useful to summaries advantages and disadvantages with the following list.

- Advantages:
    - Best dimensional and roughness achievable
    - Thin layer processable, 0.025-0.05mm
    - Solid technology until is the first one to be developed
- Disadvantages
    - Only thermosetting are processable
    - Supports are required and must be realized with the same material of component

1.4.3 DMLM

DMLM is the acronym of Direct Metal Laser Melting, and it is a Laser Powder Bed Fusion process. The energy source is a laser, or multiply lasers, and the material processed is powder of metal. A various typology of alloy can be processed. The process stars with the deposition of a thin layer of powder; the thickness of layer is 20-100 µm [23]. The laser treats the area, so it melts powder according with the STL. When the layer is finish, a mechanical system laid a new powder layer of un-used metals, and the process is repeated until the finish. [24]

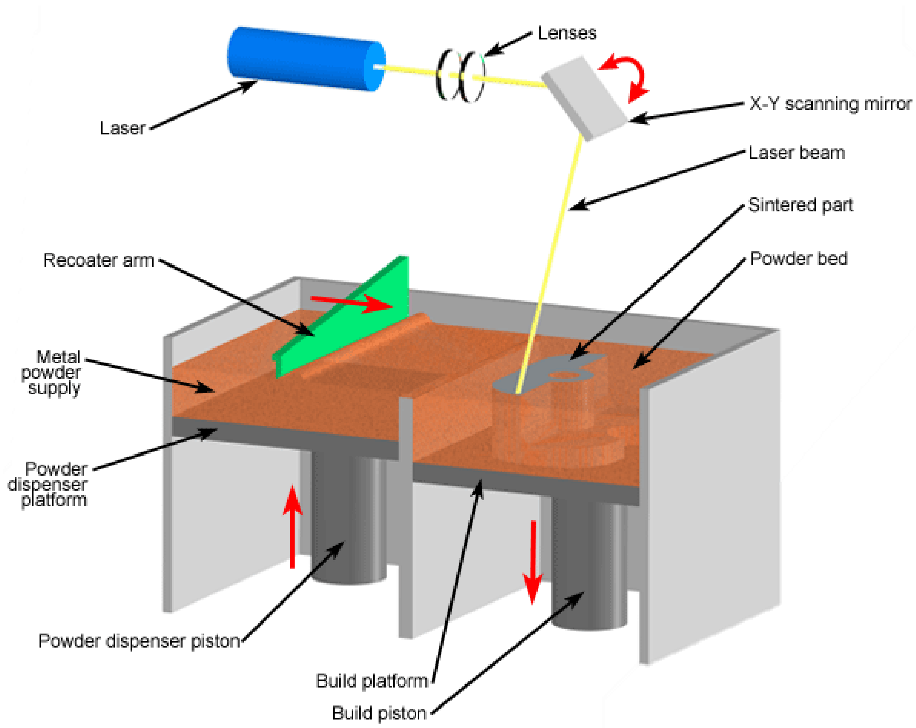


Figure 12, DMLM scheme [22]

DMLM machine have a system of lenses and mirrors (controlled with a galvanometers) to focus the laser beam and makes possible to treats all the work area of the platform. During the DMLM process, due to the high local temperatures necessary for melting, the parts are built under a controlled atmosphere to prevent oxidation and other problems that can impact to mechanical properties of the finished part [25]. The inert gases used to create the protective atmosphere are argon or nitrogen. The power of laser is between 200 and 1000W, and many typologies of laser exists, the most relevant are CO2, Nd-YAG, fiber laser, disc laser. The build platform temperature is maintained around 80-100°C. Supports are required [26].

It is useful to summaries advantages and disadvantages with the following list.

- Advantages:
    - Complex Geometry processable
    - High speed solidification which makes possible to achieve fine microstructure
    - Density achievable equal to 99.9%, which involves the absence of porosity
    - Higher surface quality respect the other PBF for metal
    - Various materials processable
- Disadvantages
    - Lower build rate respects the other PBF for metals, due to power of energy source
    - Supports required

1.4.4 EBM

EBM is the acronym of Electron Beam Melting and it is a L-PBF, too. In this case, in contrast with DMLM, the energy source is an electron beam, emitted by a heated tungsten filament, with a power around 4kW. The higher power makes possible to process layer thicker respect DMLM, it can achieve 2mm layer. There is no more the system of lenses and mirrors but thanks to two magnetic fields, a focus coil, which is a magnetic lens that focuses the beam to the desired diameter, and a deflection coil, which deflects the focused beam to the desired point on a build platform [27].

Is required to work under a high vacuum atmosphere, 10^-4 to 10^-5 Pa [28]. The supports required are less than DMLM because the working camera temperature is around 900°C, so the un-melted powder is able to sustain melted powder. The high temperature of EBM reduces the formation of thermal residual stresses in the component limiting the risk of crack formation.

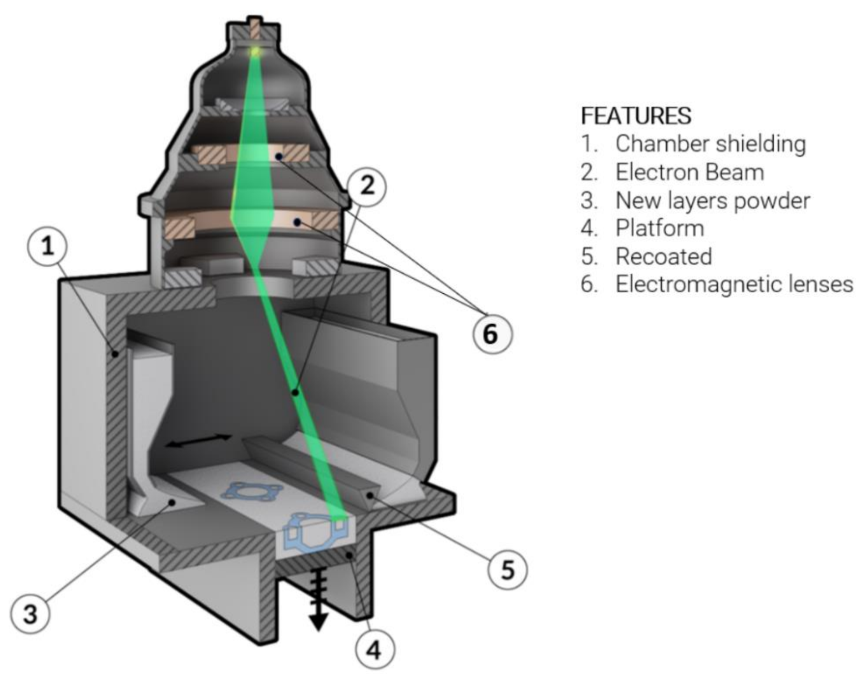


Figure 13, EBM scheme [29]

The source energy, electron beam, limits the processable materials to electro conductive material only. The most processed materials are Ti6Al4V, Inconel718, Cobalt-Chrome alloy. It is not possible to process aluminum alloy and all low melting point metals due to the tendency to evaporate, under vacuum conditions and high temperature.

It is useful to summaries advantages and disadvantages with the following list.

- Advantages:
    - Complex Geometry processable
    - Limited supports required
    - Higher speed solidification which makes possible to achieve fine microstructure
    - Higher build rate respects the other PBF for metals, due to higher power of energy source
    - Density achievable equal to 99.9%, which involves the absence of porosity
    - Low probability of crack formation and less residual stress, due to high temperature.
- Disadvantages
    - Lower surface quality respect the other PBF for metal
    - Only electric conductive materials are processable
    - Aluminum alloy and low melting point metal are not processable, due to risk of evaporate

1.4.5 DED

DED is the acronym of Direct Energy Deposition, it is also indicated as LENS or DMD. This technology is characterized by the melting of the metal powder or wire as they are deposited. The energy source is usually a laser similar for DMLM but in this case there is not the system of lens and mirror; the laser is mounted on a 4 or 5 axis arm. Two or more nozzles are united to laser and mechanical arm, so it is possible to make metal alloy directly during the printing process since each nozzle can be feed with different metal powders; or it is possible to realize component with different metals stratified. With this technology is possible to work on already existent component.

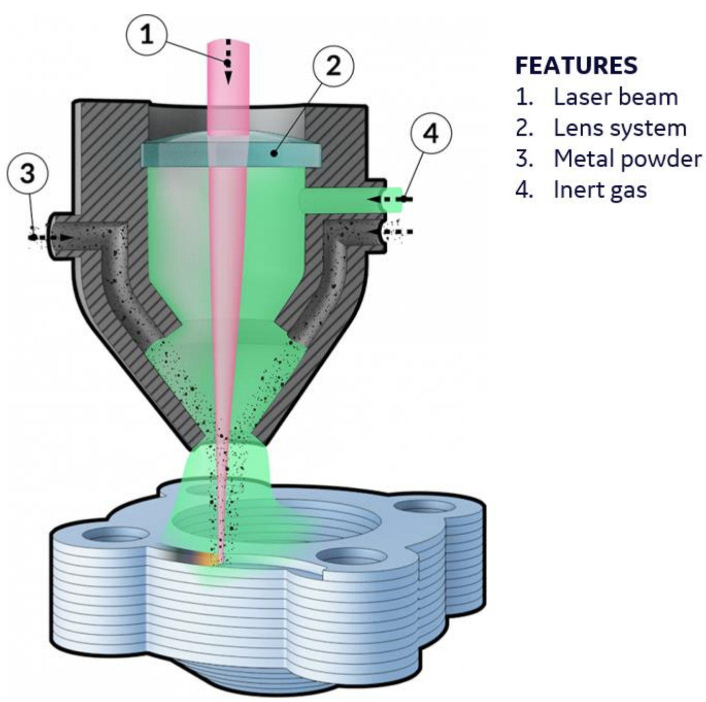


Figure 14, DED scheme [29]

An advantage of this system is that there are no limits on the size of the working volume, as deposition and melting are carried out directly on the component, so the presence of a working chamber or platform is not necessary. The large working volumes achievable makes the DED very suitable both for repairing and even for produce definitive parts.

It is useful to summaries advantages and disadvantages with the following list.

- Advantages:
  - Hypothetical unlimited working volume
  - Multiple nozzles which make possible to realize different alloy during the process
  - It is possible to work on already existent components
- Disadvantages
  - Lower surface quality respect the other AM technologies for metal
  - Limited processable geometry
  - More difficult to control oxidation due respect the other AM technologies

Chapter 2

Additive Manufacturing Process Chain

There are so many AM technologies, they can be consistently different respect each other but the process chain is composed by a series of actions which are the same for every technology. It is possible to list these steps:

1. Generate the 3D CAD
2. Export the 3D CAD in STL file
3. Prepare the Build file, including possible supports
4. Machine setup and job execution
5. Part removal and cleanup
6. Post processing and finishing

Figure 15, additive manufacturing process chain

AM technologies are constantly evolving, so the associated technologies are evolving too. During these last years, the tool of process simulation became always more useful. It is ad optional step, between steps 3 and 4. This can prevent printing errors and that may result in discarded parts that means loss of money and time. Another important tool recently developed is Compensation. This one can be actuated by simulation or by measurement and it is a step that can be actuated after Simulation step or after finishing and scanning of processed part. It is useful to avoid distortions and surface problems, it can decrease the post processing required, too.

2.1 Generate the 3D CAD

The first step of AM Process Chain is the translation of concept, of idea into a computer file. So, it is used CAD, Computer Aided Design, model. This is a virtual representation of idea, which is realized by a Boolean combination of elementary geometry and shape.

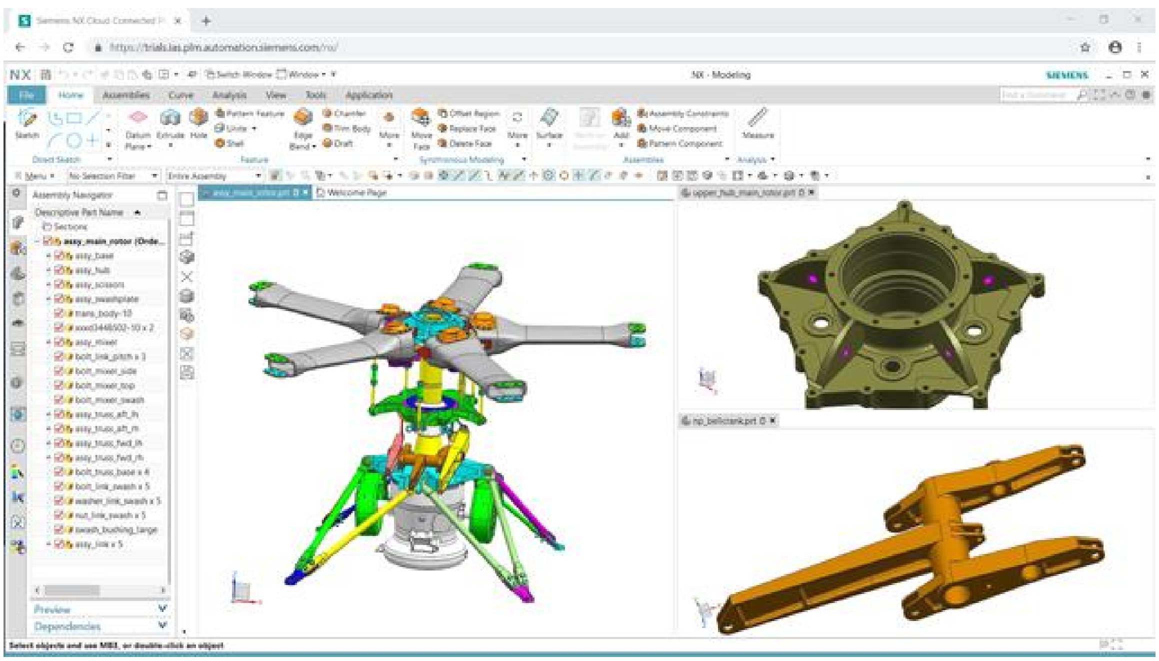


Figure 16, example of CAD program [30]

Though the process chain typically progresses in one direction that starts with CAD modeling and ends with a finished part or prototype, but generally this is an iterative process, where changes to the CAD model and design are made to reflect feedback from each step of the cycle chain. Specific to the metal powder bed technology, critical feedback can come from geometry and property anisotropy on parts due to build orientation, distortion of part or features due to thermal history of build, issues in generating and removal of support structures. So, it is usually required to modify the original CAD model to answer process issue.

2.2 Export the 3D CAD in STL file

STL is the acronym of Standard triangulation Languages. It is common file format given as input in pre-process AM program. The format of STL is binary or ASCII and it represents a solid whose surface that has been discretized into triangles. The discretization implicates a non-perfect conversation of CAD model. In this last typology file, the curves are perfect but in STL file they are represents as a multitude of short segments. To avoid the non-perfect conversation can be pass through the increase of element triangles used [31].

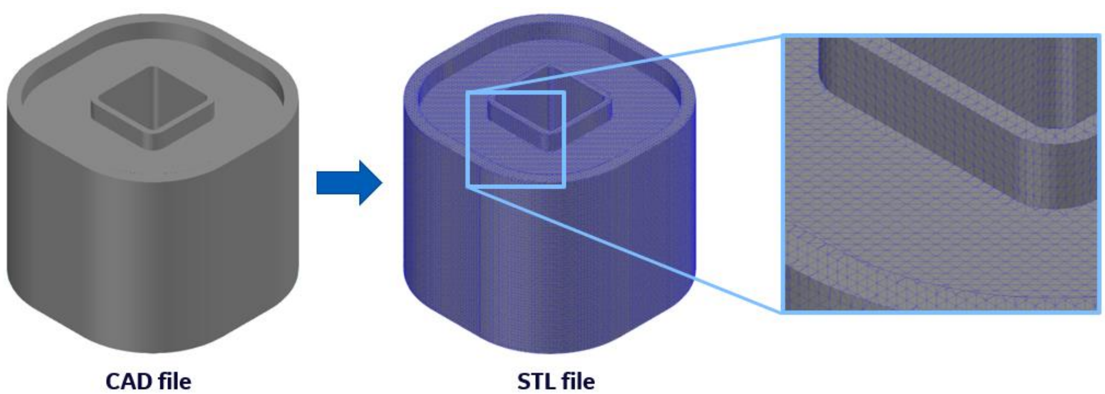


Figure 17, CAD-STL comparison

The limit of STL file is that contain only geometrical information, so material properties cannot be stored. The “AMF” format was developed specifically to avid these limitations, indeed is now the ASTM/ISO standard format. It contains geometry information, dimensions, color, material, and additional information is also possible with this file format. However, the predominate format of file used is still the STL format [32] [33].

The conversation from 3D CAD file to STL file Is usually realized by CAD parametric programs, where CAD file was realized.

2.3 Prepare the Build file

The preparation of build file is usually realized using a pre-process program. Two examples of this typology of program are Magics and Netfab.

During the conversation from 3D CAD file to STL may be generated some errors, so the first step for preparation of build file is to verify the STL file and eventually correct it. The most common errors of STL are between cells, internal wall, intersection of triangles or inverted normal. Pre-process programs usually are able to automatically repair the errors but, in some cases, they require to be manually corrected. STL problem’s correction is an important step to avoid error that could lead to rejection of the build with both economic and time-consuming consequences.

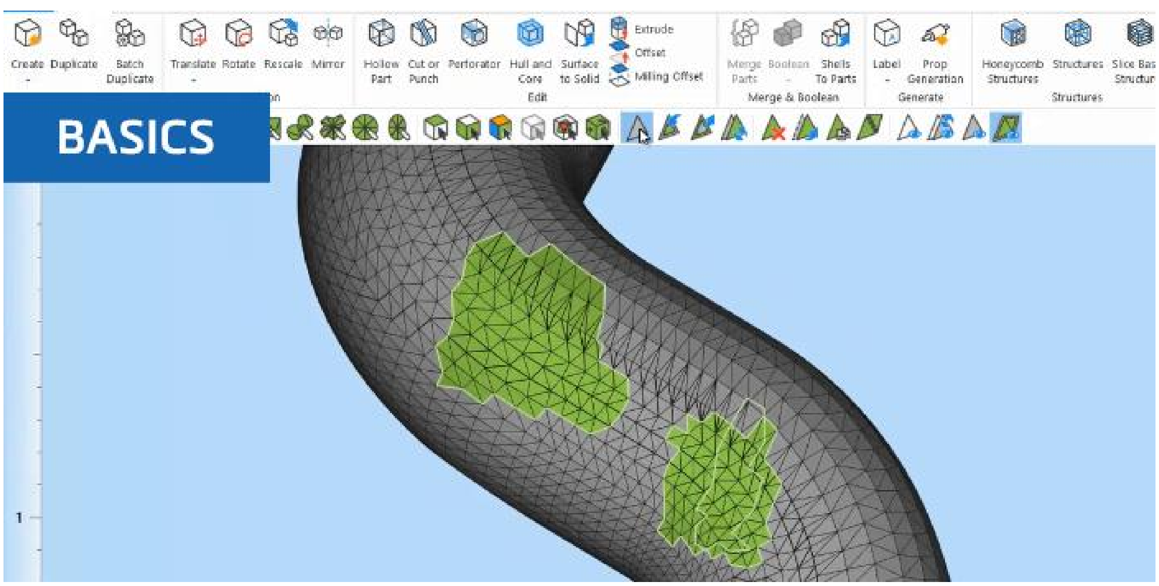


Figure 18, example of STL repair operation [34]

The second step of build file preparation is the orientation of the component. This step is strongly influent for the time job required. 3D printing processes usually have two different speeds of execution in the x-y plane and in the z direction. Different orientations surely differ in terms of number of layers and, as consequence, of time needed in the entire process [35].

Supports has many different tasks, one of them is to support all the parts that sticks out. Another one is to makes united the component to the build plate, over where is used [36]. Many supports typologies exist, and they can be automatically produced by pre-process program. The user must give to the program many input parameters. Obviously, supports can be manually realized with CAD programs, too.

Until the STL is verified, oriented and supports are generated, so it is possible to continue with the slicing. The slicer program has the task to produce a finite succession of layer. These represents the intersected area of build (part/parts and supports) with planes parallels to x-y plane. The thickness of the layers influences the number of layers and the quality of result.

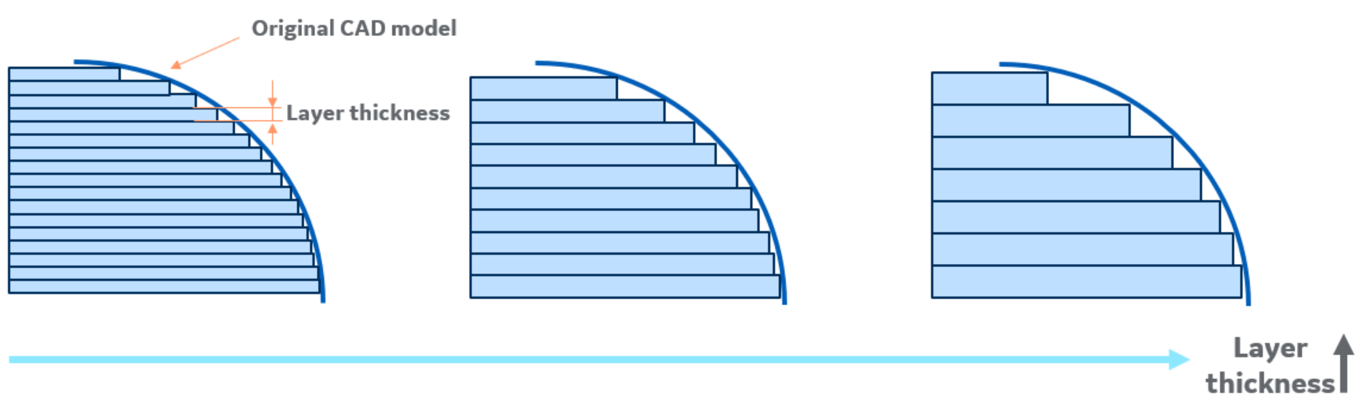


Figure 19, different layer thickness to slice the same part

The slicing can be uniform or adaptive. The second one is able to reduce the thickness of layer only where is required.

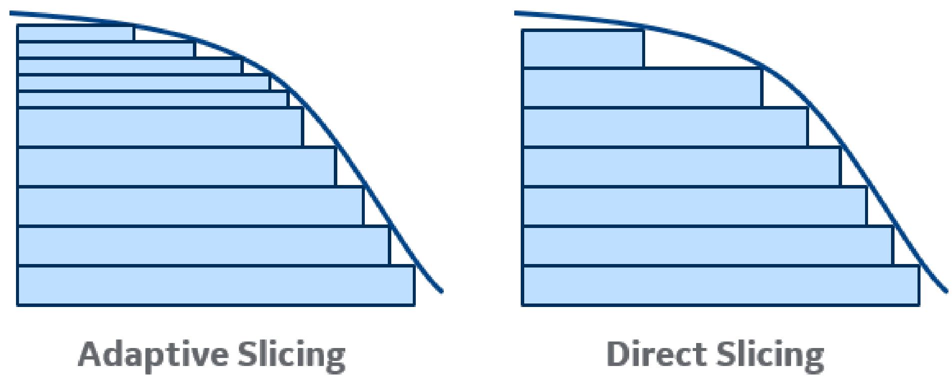


Figure 20, direct and adaptive slicing

2.4 Machine setup and job execution

It is possible to conceptual divide this step as the succession of machine setup and process parameters control.

Must be verified that process chamber is cleaned from last job, must controlled machine's sensor and refilled raw material required, included eventually inert gas.

At this moment it is necessary to set the process parameters. Each AM technology has a different parameter set to impose. Few general parameters are: material processed, power of energy source, velocity, many temperature, eventually flus of inert gas. So, it is possible to start the job. The time required is function of many parameters: technology, geometry of component, material, layer thickness.

During the execution of job is necessary to monitor the process parameters. The oxygen level is one of them for many AM technologies. If it is bigger than 1-2% many oxidation problems can be compare, so the job is stopped. The monitor of melt pool detects the intensity of the emission of the thermal radiation from the melt-pool and does basic analysis on the size and radiation intensity distribution of that.

2.5 Part Removal and cleanup

Some AM technologies require, when the job is completed, to wait a interlock. For example, PBF require that the temperature in execution chamber go down in a controlled way. The untreated raw material must be separated from the treated part. The loose raw material from one process can be recycled and goes through a series of sieving steps to remove contaminates and unwanted particulates. It is required an experienced manual manipulation and the operator must use the necessary DPI: gloves, protective suit, eye-protector, oxygenated mask. They depend on the AM technology used.

Figure 21, operator during the removing of untreated powder [37]

Once the loose powder is removed from the finished part, the build is ready for post-process.

2.6 Post processing and finishing

Post processing and finishing operations are multiple and are strongly influenced by the material processed, the AM technology used, and the characteristic required. For metals parts processed with PBF technologies, it is usually required a first thermal treatment to decrease the mechanical stress. After that, it is possible to remove the parts and supports from the build plate. An EDM cut is commonly used for this operation. So, supports must be removed and it is required high knowledge and experienced manual manipulation. It is possible to continue with all mechanical operations, as sandblasting, eventually drilling, treading. Now it is time for eventually last thermal treatment and the part is ready.

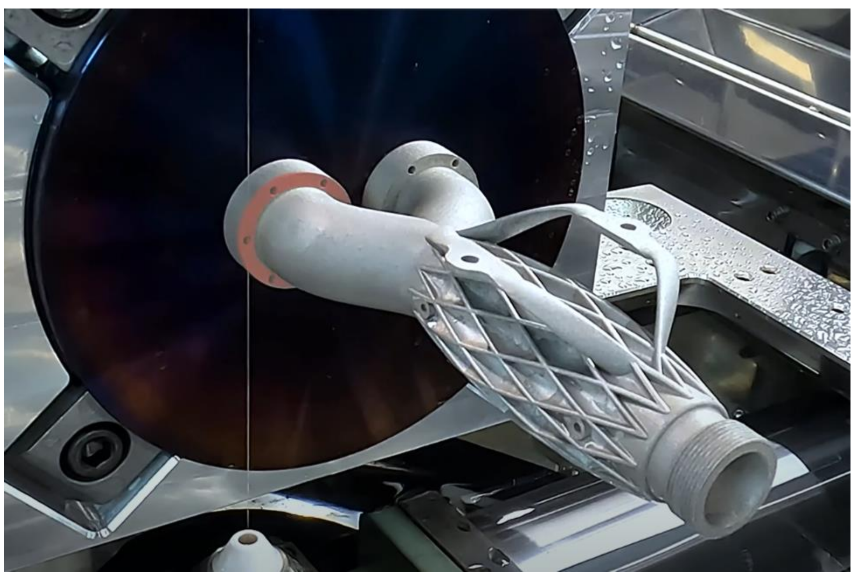


Figure 22, EDM cut of DMLM processed part [38]

Polymeric components required different operations; they usually do not need thermal treatment, but SLA parts must be received an UV oven treatment. FDM parts can require to be separated from supports and it can be do with a water tank until the supports are water-soluble.

Parts can receive an ultimate operation as painting, polishing, vacuum metallization.

It depends on the tasks required.

Chapter 3

Global and local defects

Even if PBF is probably the most developed technology for metal additive production, it has some limits. The volumetric shrinkage implicates two typologies of defects: global and local. Obviously, the volumetric shrinkage is not the only factor that determinate the presence and the magnitude of defects. Geometry, material, technology influence the result, too.

Global defects consist in geometrical deformations. So, the component printed does not perfectly fits with nominal geometry. It can be a problem for functional zones whit a high level of dimensional tolerance required. This typology of defect can be easily observed trough deviation map, as shown in Figure 23.

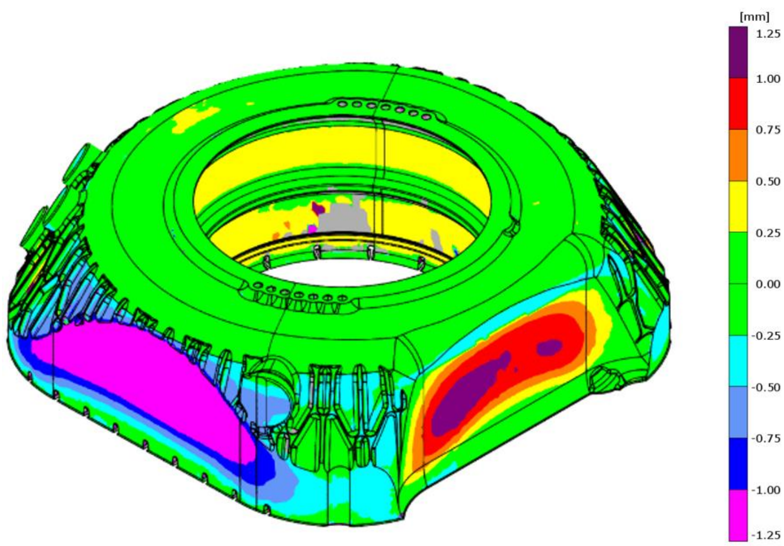


Figure 23, example of deviation map

In Figure 23, only the green colored zones have a good dimensional fit between Nominal geometry and Measured component. In pink and red colored zone the measured component undergoes or overgoes more than 1mm respect the Nominal one.

On the other hand, local defects are more precise respect global. Exists many possible local defects but the core of this thesis is on local defects caused by volumetric shrinkage, geometrical and material characteristic. They look like horizontal line on the component. Indeed, from now on they will be called Build Line.

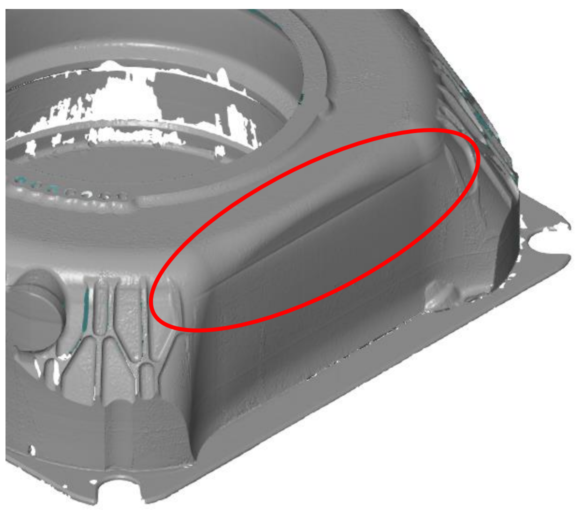


Figure 24, example of local defect

Let's focus on the factors which determinate build lines. These are mostly three:

- Volumetric shrinkage due to gradients of temperature
- Geometrical characteristic
- Material properties

The volumetric shrinkage translates the gradients of temperature in compression or decompression of material. The gradients of temperature during process are function of the technology. L-PBF and EBM have a huge different gradient of temperature.

The volume shrinkage alone cannot cause a build line. It is necessary a particular geometrical condition: huge undivided area processed variation of consequent layers. An example is an internal hole which ends.

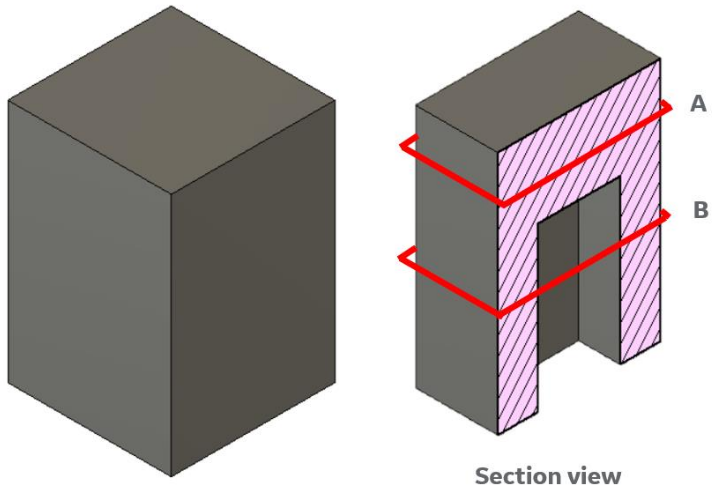


Figure 25, example of internal hole

In corresponding of the end of the internal hole, the undivided area processed increase. So, we can predict that a build line in that height will appear.

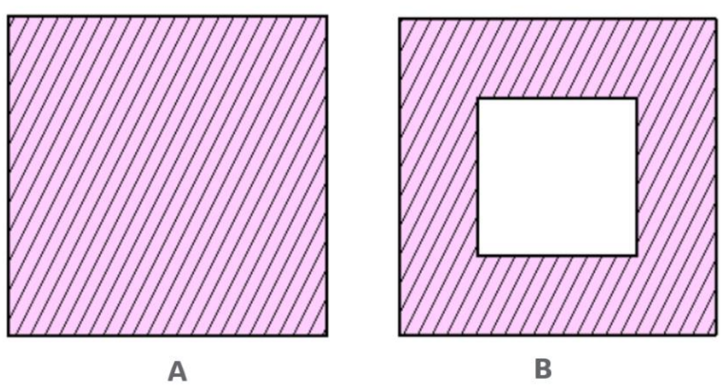


Figure 26, example of increment of undivided area

The material influences the magnitude of this phenom. In particular, the volumetric shrinkage coefficient, combined with the process parameters and geometry, determinate the impact of this defect.

3.1 Build Line Parameters

To describe the defect of build line is necessary to define parameters. In particular, three parameters are defined:

1. Delta inclination
2. Sharpness
3. Magnitude

3.1.1 Delta inclination

The Delta Inclination parameter determinates the presence of a build line and can give an idea about the intensity of the phenom.

To determinate the Delta inclination it is necessary to work on deviation data. It is possible to divide the procedure into six steps:

1. Import Nominal Geometry and Measured Geometry on an inspection program.

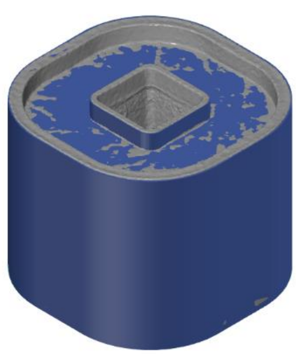


Figure 27, example of Import Nominal Geometry step

2. Calculate the deviations of Measured respect the Nominal.

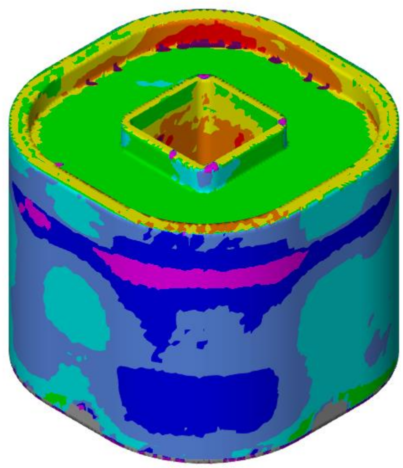


Figure 28, example of deviation map

3. Consider a representative section.

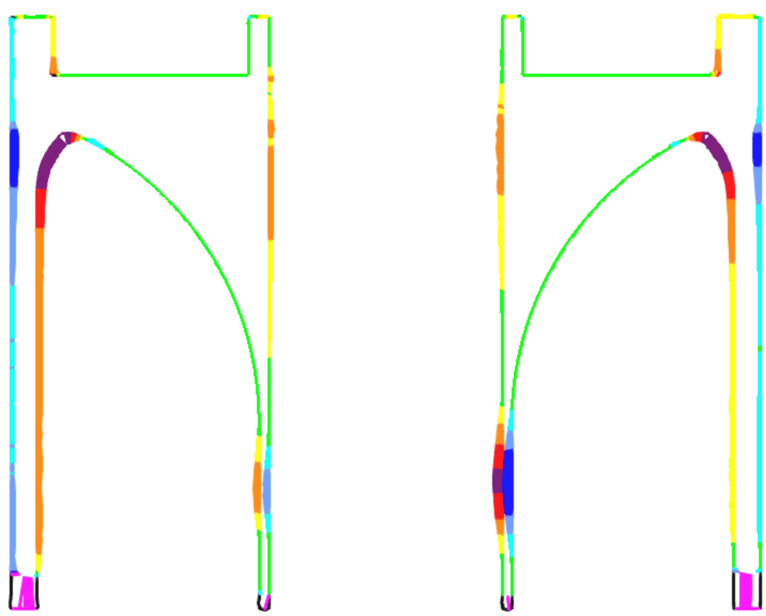


Figure 29, example of deviation section

4. Catch the height of build line center and discretize the section with 1mm height intervals.

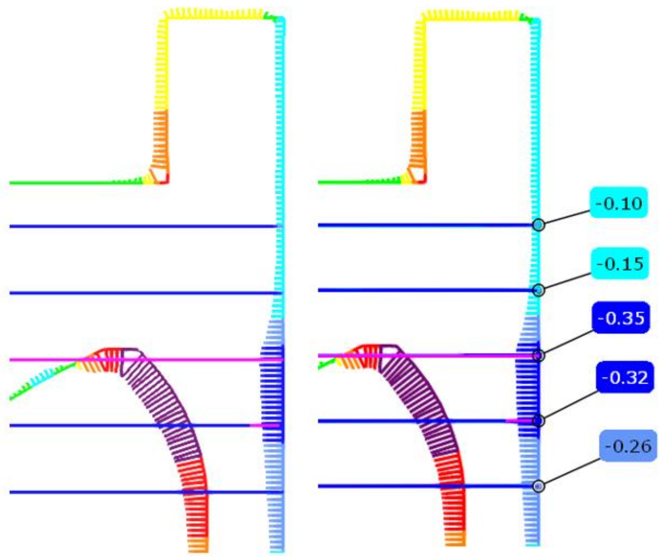


Figure 30, example of discretization of deviation section

5. Determinate the deviation at each interval: d^{+1}, d^{rif}, d^{-1} *and so on.* Deviations can be absolute or relative, it doesn't matter.
6. Calculate the delta inclination with the following formula:

$$\Delta^{\circ rif} = \left(\frac{\arctan(d^{+1} - d^{rif})}{\pi} * 180\right) - \left(\frac{\arctan(d^{rif} - d^{-1})}{\pi} * 180\right)$$

The value of delta inclination for the case represented in Figure 30 is shown in below chart.

Table 1, example of delta inclination

	deviation [mm]	Δ^°
d^+2	-0.10	
d^+1	-0.15	-8
d^rif	-0.35	13
d^-1	-0.32	2
d^-2	-0.26	

In corresponding of the build line center, the value of delta inclination is equal to 13 degrees, bigger than the values of consecutive and previous interval.

The build line is more defined as much the delta inclination is bigger.

3.1.2 Sharpness

The Sharpness is the parameter which represents the punctuality of shape.

To determinate Sharpness it is necessary to work on deviation data, too. It is possible to divide the procedure into six steps:

1. Import Nominal Geometry and Measured geometry on an inspection program.
2. Calculate the deviations of Measured respect the Nominal.
3. Consider a representative section.
4. Catch the height of build line center and discretize the section with 1mm height intervals.

5. Determinate the deviation at each interval: d^{+1}, d^{rif}, d^{-1} *and so on*.
   Deviations had to be expressed respect the deviation value at the build line center height.

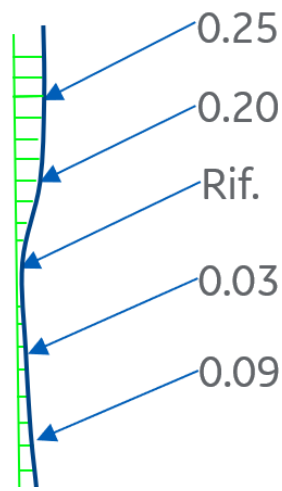


Figure 31, example of relative deviation section

6. Determinate the value of sharpness as the absolute value of the sum of d^{+1} and d^{-1}:

$$Sh = |d^{-1} + d^{1}|$$

The value of Sharpness for the case represented in Figure 31 is shown in below chart.

Table 2, example pf sharpness

	Deviation relative [mm]
d^+2	0.25
d^+1	0.20
d^rif	0.00
d^-1	0.03
d^-2	0.09

Sh =	0.23mm

The build line presents a more punctuality shape as much the Sharpness is bigger. The comparison of Sharpness value respects the deviation value of d^{+1} and d^{-1} can give an idea about the symmetry o the phenom.

In below there are three examples of different section to deeply understand what sharpness represents.

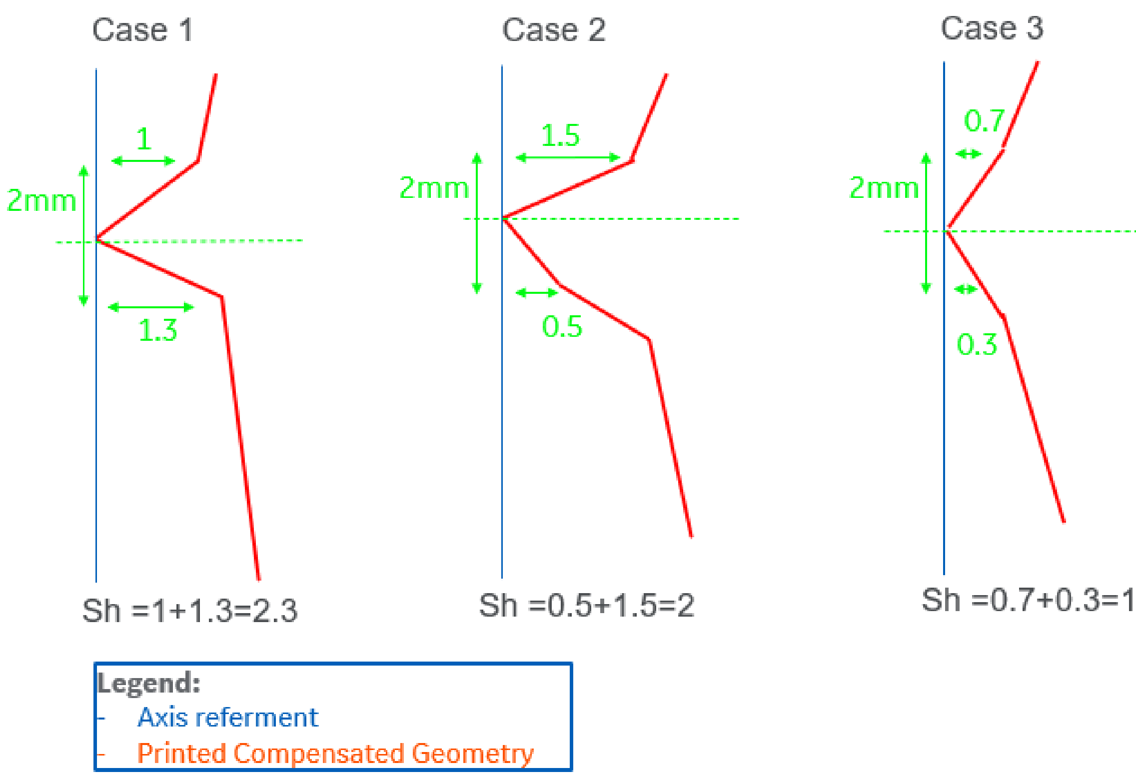


Figure 32, sections with different sharpness

3.1.3 Magnitude

The Magnitude is the parameter which express the level of impact of the build line.

To determinate Magnitude it is necessary to work on deviation data, too. It is possible to divide the procedure into six steps:

1. Import Nominal Geometry and Measured geometry on an inspection program
2. Calculate the deviations of Measured respect the Nominal
3. Consider a representative section

4. Catch the height of build line center and discretize the section with 1mm height intervals
5. Determinate the deviation at each interval: d^{+1}, d^{rif}, d^{-1} *and so on*. Deviations had to be expressed respect the deviation value at the build line center height.

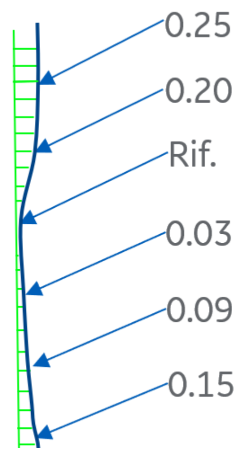


Figure 33, example of relative deviation section

6. Determinate the value of sharpness as the maximum absolute value of the sum of two deviation heights distant 5mm and build line center must be included in the interval.

$$Mg = |d^{x} + d^{x+5}|$$

With: $x < rif < x + 5$

The value of Magnitude for the case represented in Figure 33 is shown in below chart.

Table 3, example of magnitude

	Deviation relative [mm]
d^+3	0.24
d^+2	0.25
d^+1	0.20
d^rif	0.00

Mg = 0.40mm

d^-1	0.03
d^-2	0.09
d^-3	0.15

In below there are three examples of different section to deeply understand what sharpness represents.

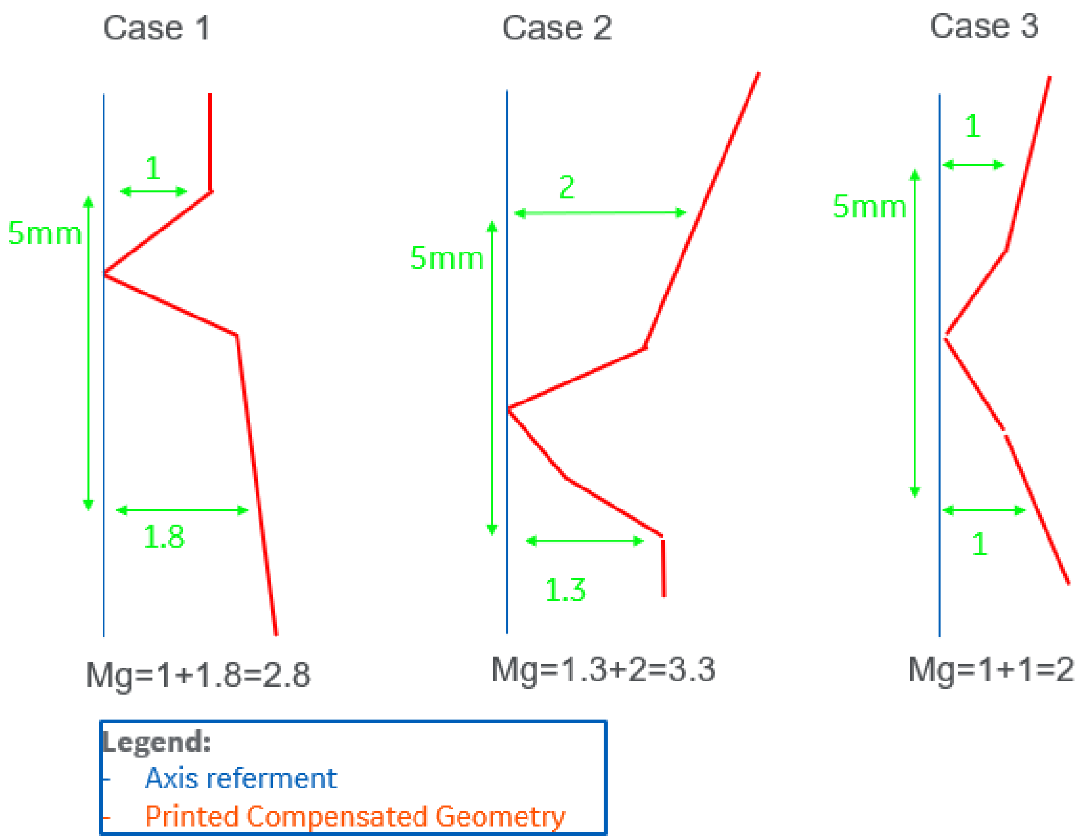


Figure 34, sections with different magnitude

Chapter 4

Compensation

To make a more understandable narration, it is useful to list three definitions:

- Nominal Geometry: it is the perfect geometry, realized through a CAD program.
- Deformed Geometry: the nominal geometry is printed, scanned, and polygonised. Before the scan step the printed component could receive a stress realize and EDM cut.
- Compensated Geometry: it is the result of compensation, and it is a STL file.

Figure 35, Nominal, Deformed and Compensated geometries

The geometrical compensation is the practical solution used to resolve, or at list to reduce, the geometrical deformation, local and global, of parts produced with PBF technologies.

Until PBF technologies temperature is higher respect ambient temperature it causes deformation. The goal is to generate a compensated geometry that its printed and deformed result will fits with the nominal geometry.

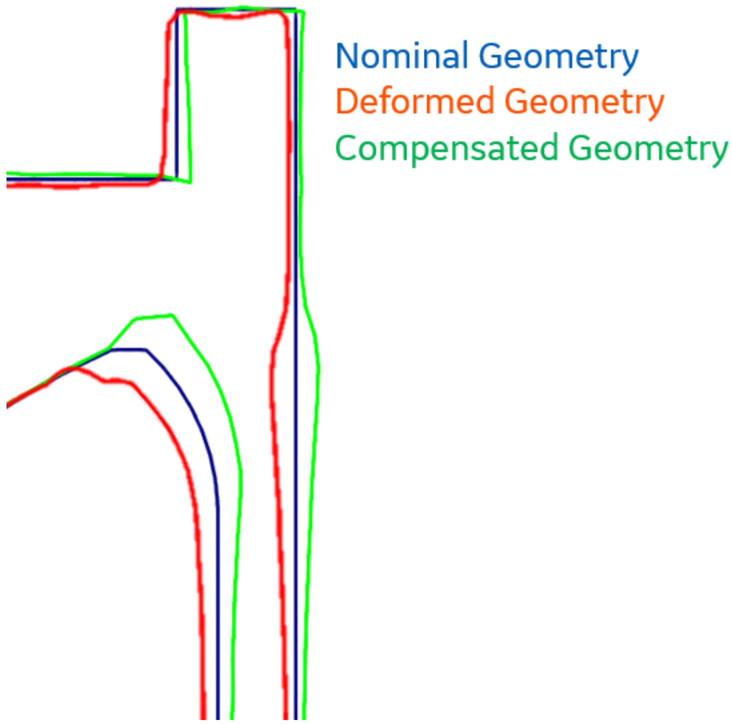


Figure 36, sections of Nominal, Deformed and Compensated geometries

To realize the compensated geometry that it will be processed, there are three ways:

- Compensation by Measurement
- Compensation by Simulation
- Hybrid compensation

4.1 Compensation by Measurement

The concept of compensation by measurement is to measure the deformed geometry and apply the inverse of deviation to the nominal. In particular, the steps required are listed below:

1. Process the Nominal Geometry
2. Scan the Deformed Geometry and obtain a points cloud
3. Polygonise the points cloud into STL
4. Generate the deviation of Deformed Geometry respect Nominal Geometry
5. Apply the inverse of deviation to nominal to obtain the STL file of Compensated Geometry
6. Process the Compensated geometry
7. Scan, polygonise, compare the Compensated geometry processed
8. If the results of comparison are acceptable, the compensation is finish. Otherwise, is required to restart from step n.4

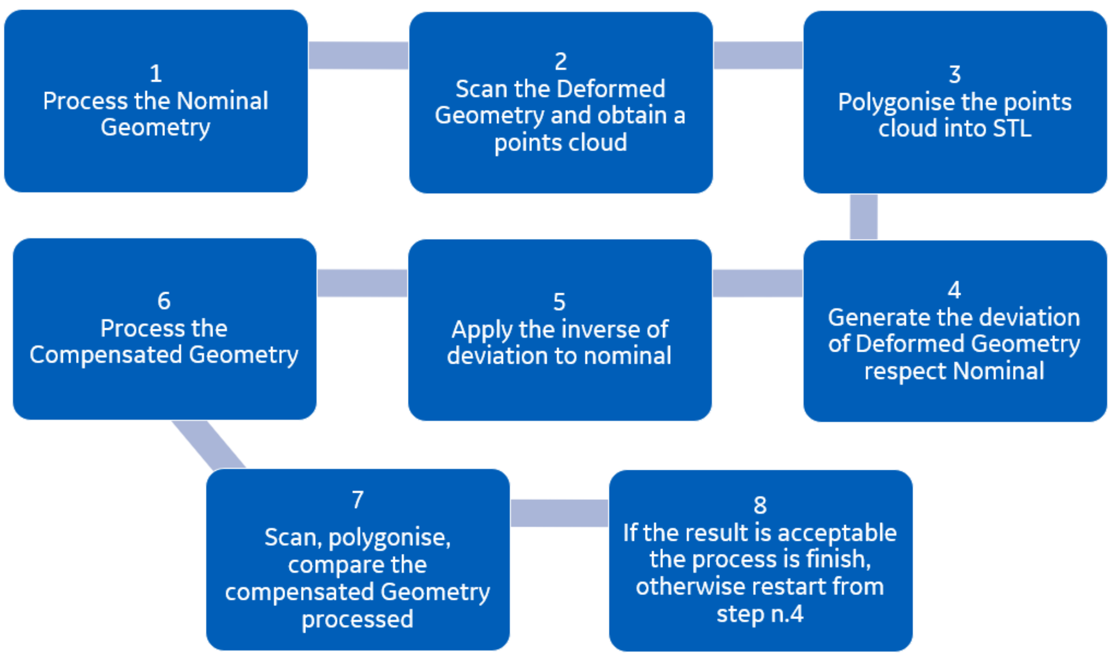


Chart 1, compensation by measurement

Until the deformation is measured, it is more reliable respect the deformation estimates by simulation. On the other hand, it requires to process a first unused job. So, it is expensive and time demanding. To improve the result is required to perform an additional iteration of compensation, so it is required to process another job.

4.1.1 Compensation by measurement parameters

In the case of compensation by measurement, the compensation is acted by a CAD program tool. It requires the nominal geometry as STL file and the deviation of deformed geometry, as ascii file. The parameters which had to be chosen are:

- Build Plate Constraints
- Definition of volumes
- Magnitude and reliability

4.1.2 Build Plate Constraints

The build plate rigidity influences the firsts layers. It increases the rigidity of below portion of part processed. Indeed, the deviation of below part of part is less than the remaining part. So, the compensation should not be applied on below part, influenced by rigidity of build plate.

It is figured below the effects of build plate constraints. The images are the representation of deviation of compensated geometries respect the nominal one. The image (a) shows how the firsts layers are not compensated. This is what desired. The image (b) shows that only few layers are not compensated, like image (c) where build plate constraints are not applied.

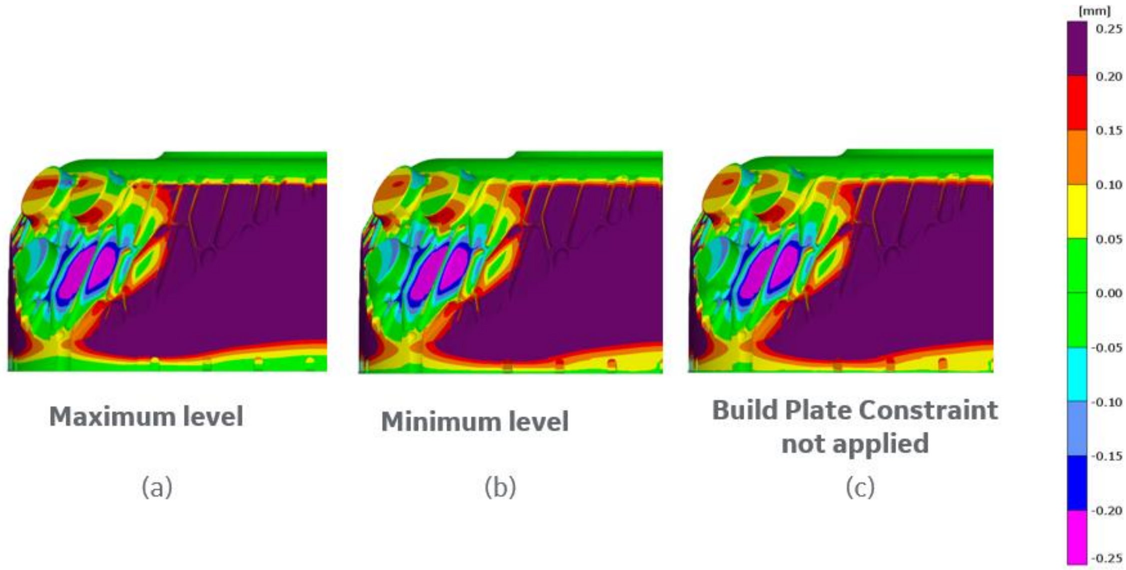


Figure 37, comparison of build plate constraints effects

It is important to consider that the magnitude of stiffening given by build plate, is function of many aspects. Build plate thickness, build plate material, job parameters, material processed, geometry processed, supports. These are only few aspects that influence this phenom. So, it is necessary to set it for each single job.

4.1.3 Definition of volumes

There are many typologies of defects that characterized PBF jobs. They can be global or local and they can have different magnitude. So, it is useful to define more volumes and compensate each volume with different parameters (magnitude and reliability of the next chapter).

For example, in the following image, it is possible to see the local defect on the measured geometry. So, it is defined a volume which circumscribes the defect. In this way is possible to define different parameters respect the remain part compensation.

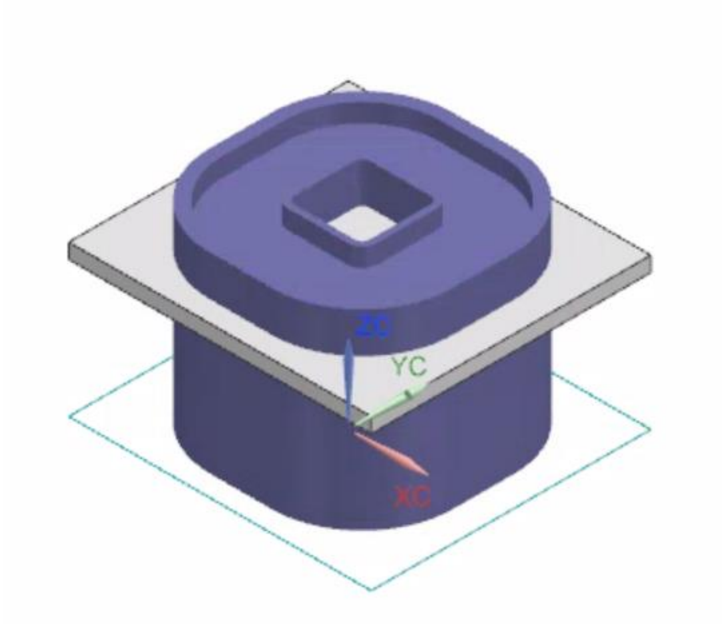


Figure 38, definition of volumes

4.1.4 Magnitude and reliability

Compensation consists in the application of the inverse deviation measured to the nominal geometry. It is not usually applied exactly. The user can define a magnitude and a reliability of deviation compensation.

The magnitude represents the scale factor applied to deviation measured. If it is equal to 100% so the compensation will be equal and inverse respect deformation. If magnitude is less the 100% so the deviation of compensation will be smaller than deviation of deformed. It is represented in the following image.

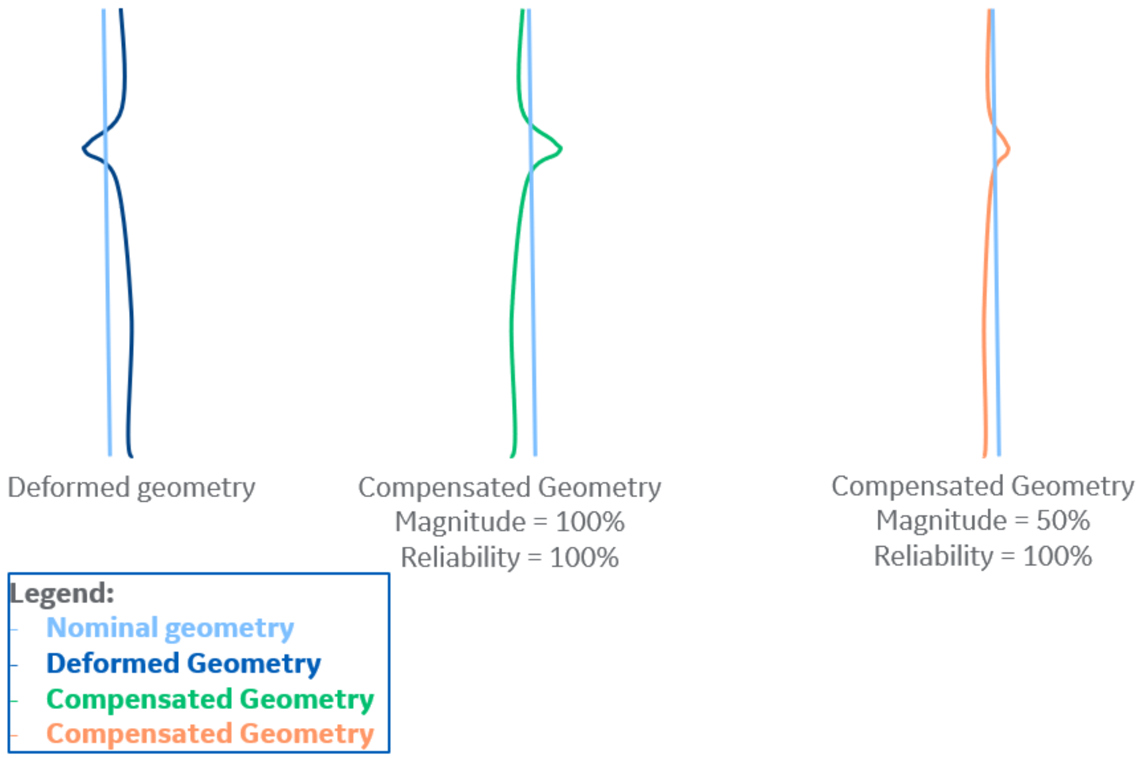


Figure 39, section comparison of different magnitude

The reliability indicates the actual reliability of deviation of deformed geometry given to CAD program. If reliability is equal to 100% so the program will compensate all points with the exact value of corresponding deviation. But if reliability is less than 100%, so the program will ignore the values of deviation highest and will create a medium deviation. It is a sort of clean step of deviation values. The result, the compensation, it looks softer if reliability is low and it looks more edgy if reliability is high.

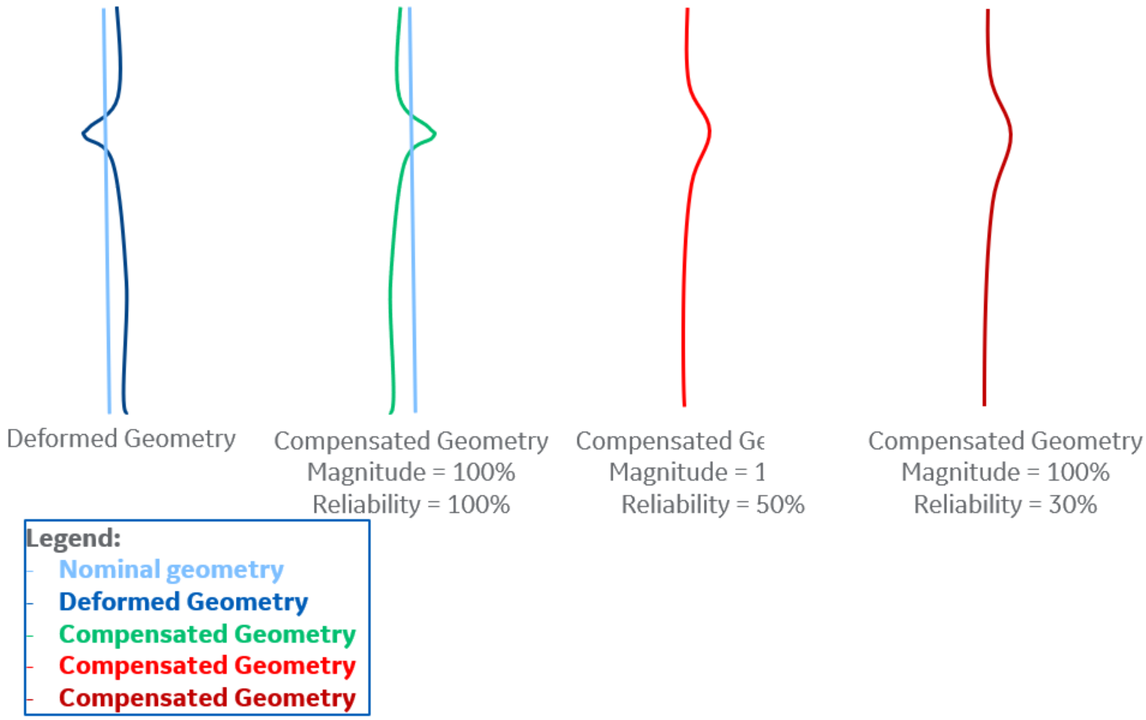


Figure 40, section comparison of different reliability

4.2 Compensation by Simulation

The concept of compensation by simulation is to simulate the process of the nominal geometry and apply the inverse of deviation to the nominal. The simulation program is able simulate and apply the deviation to the nominal geometry. It can simulate the compensation and estimates the deviation respect nominal, too. So, it iterates many times. [39]

This makes possible to compensate a component without any unused job processed. It potentially can save money and time. On the other hand, it not always able to predict the behavior of part during the process until it is a developing tool.

The steps required for compensation by simulation are listed below:

1. Generate the compensated geometry by the simulation program
2. Process the Compensated Geometry

3. Scan, polygonise, compare the Compensated geometry processed with the Nominal Geometry

4. If the results of comparison are acceptable, the compensation is finish. Otherwise, is required to change typology of compensation.

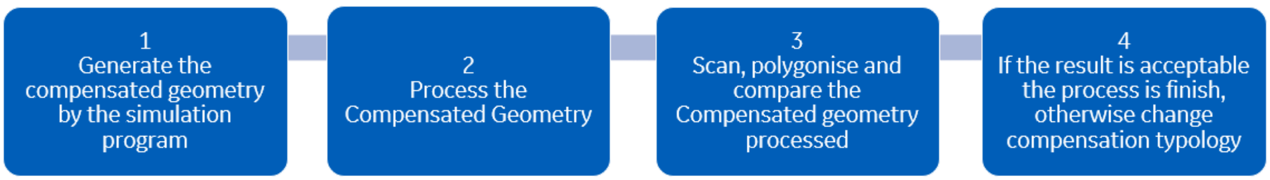


Chart 2, compensation by simulation

4.2.1 Compensation by simulation parameters

In the case of compensation by simulation, the compensation is automatically acted by a process simulation program. It requires the nominal geometry as STL file, parameters process file (energy source power, strategy scan, temperatures, layer thickness etc..) and the FEM parameters file (element size, number of iterations, etc..). The first and second files are imposed by the job process in analysis. The third file is the only one which contains settable parameters. About these last, the mainly are listed below:

- Element size
- Analysis speed
- Number of iterations
- Build plate stiffness

4.2.2 Element size

This is probably the most influence parameter. It indicates the maximum element size of the mesh that will create to represents the Nominal Geometry. The ideal element size is function of geometry and dimension. It was noted that exist a specific value of element size for each geometry, under which the simulation overestimates the deformation and over which the simulation is not reliable.

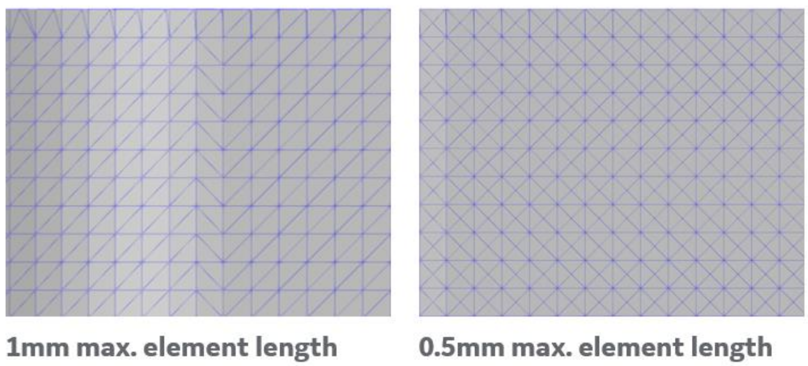
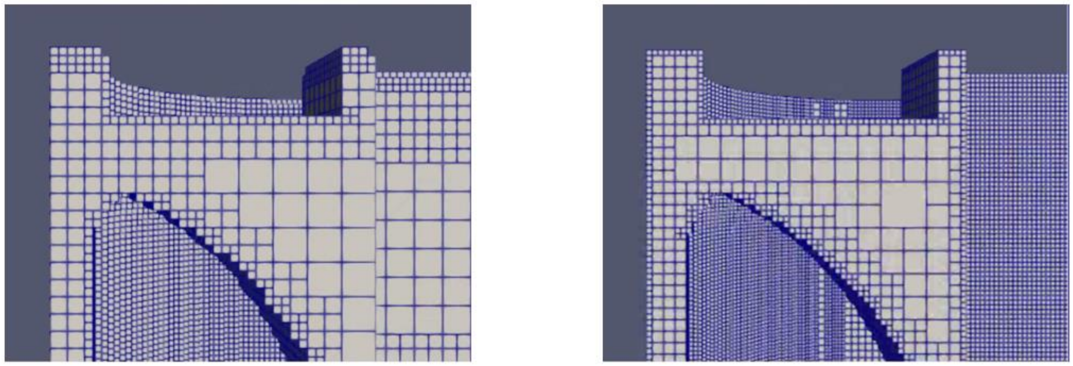


Figure 41, comparison of different element length

4.2.3 Analysis speed

Simulation time required is function of element size, geometry and dimension of part and analysis speed. This last parameter influences many operations of simulator, and it can increase the accuracy of simulation if it is imposed slower. In particular, it influences the vortex dimension.



0.4mm min. wall
normal
Number of cells: 119000

0.4mm min. wall
accurate
Number of cells: 287500

Figure 42, comparison of different cells in function of analysis speed

4.2.4 Number of iterations

This parameter represents number of iterations to generate the Compensated Geometry. This value depends on mesh size, component dimension and convergence criteria.

4.2.5 Build plate stiffness

The build plate is a massive body with a high stiffness. The simulation can consider or ignore the effect of build plate. The operator can impose the dimension and material of build plate, so, he can impose the stiffness of it.

4.3 Hybrid Compensation

The hybrid compensation is the combination of different steps of compensation by measurement and by simulation. There are many different possible combinations. It is possible to apply the compensation by simulation and, after the process of compensated simulation, apply an iteration of compensation by measurement. It is possible to simulate the process with the simulation program and manually apply the deviation, as done for compensation by measurement, to generate the compensated geometry.

The deformations are function of many and many factors. Geometry of part, material, process parameters, technology used, these are some factors. So, deformation change each job.

Chapter 5

Compensation of Canonical model

The Canonical Model is a geometry typically used in Avio Aero to realize many tests. So, in this time it is used to apply all the compensation workflows. Nominal and Measured geometries are represented below.

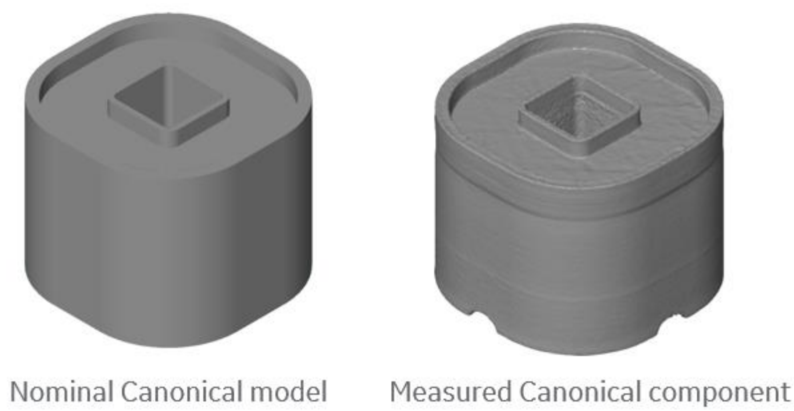


Figure 43, Nominal and Measured Canonical model

The deformed and measured geometry is obtained by L-PBF, and the material is an Inconel. It is possible to observe how the measured geometry has visible defects. In figure below are represented the deviations.

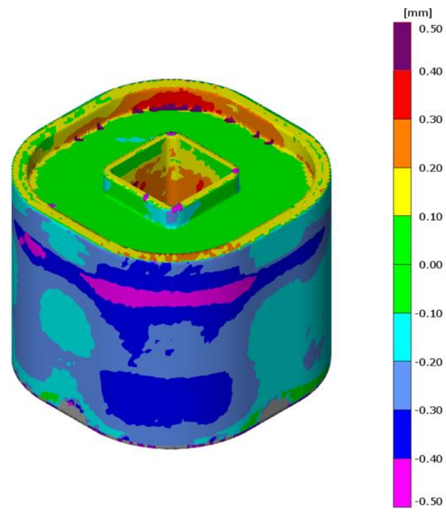


Figure 44, deviation of measured component

The goal of compensation is to reduce the general deviation and to avoid the local defect, circled in below.

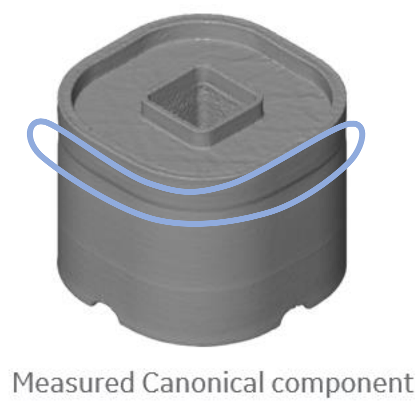


Figure 45, local defects on measured component

5.1 Compensation by simulation

The first necessary step to act the simulation is to prepare:

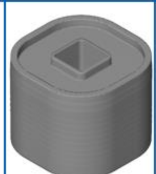
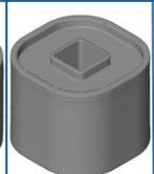
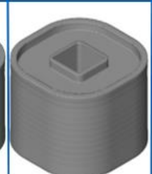
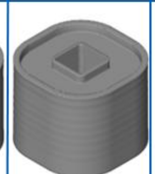
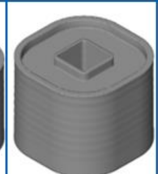
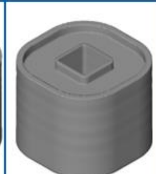
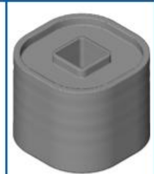
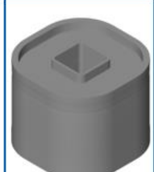
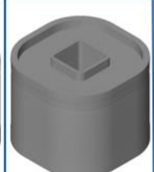
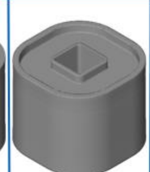
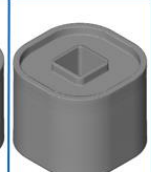
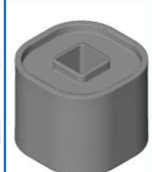
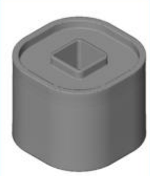
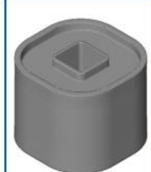
- Nominal Geometry STL
- Process parameters file

- Simulation parameters

The first and second files are easily prepared because it is not an active-mind action in this case. The operator had to digit all process parameters used to process the nominal geometry. The third file require more accuracy, because there is no evidence to know the optimal value of element size o number of iterations.

Until the nominal geometry is already processed, it is possible to run many simulations with different element sizes and detect the optimal one. In particular, I realized 14 simulations, which have different element size and analysis speed. The resume table of simulation is below.

Table 4, resume of canonical model process simulation

Analysis Speed \ Min. Wall	0.2mm	0.4mm	0.6mm	0.8mm	1.0mm	1.2mm	1.4mm
Normal							
Accurate							

All normal speed analysis are characterized by a wavy surface. The defect is represented in Figure 46.

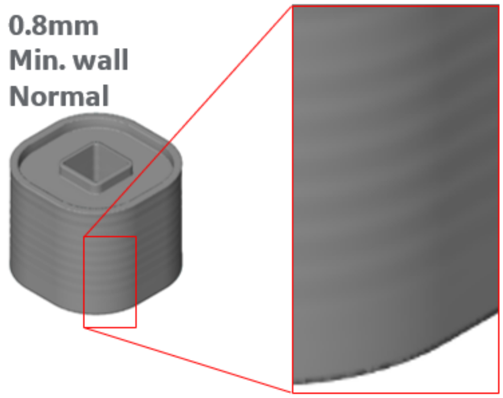


Figure 46, surface defect on simulated

It is easier to observe this surface defect on Paraview, Figure 47.

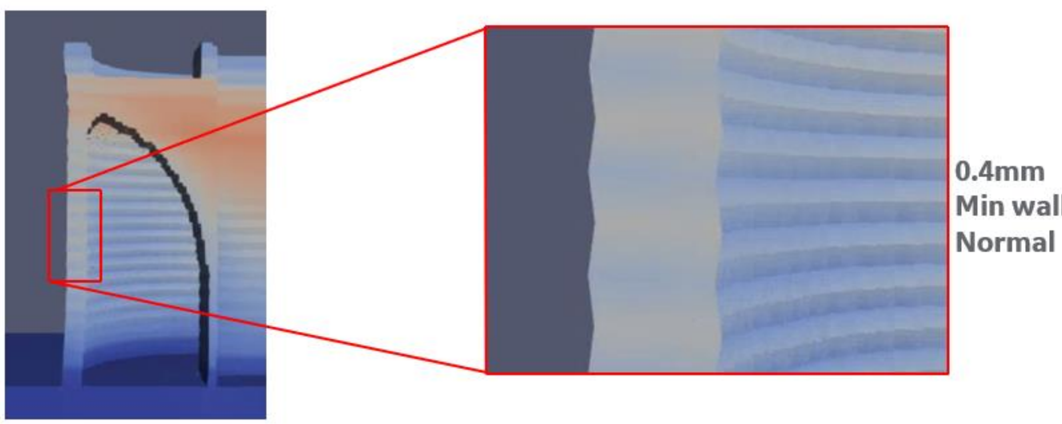


Figure 47, detail of surface defect on simulated

So, it is not possible to use normal analysis speed simulations. To understand which simulation represents better the case of study, it is useful to detect the deviation of many relevant points on simulated. In Figure 48 is possible to observe the deviation of many relevant points from Deformed measured component respect the nominal one.

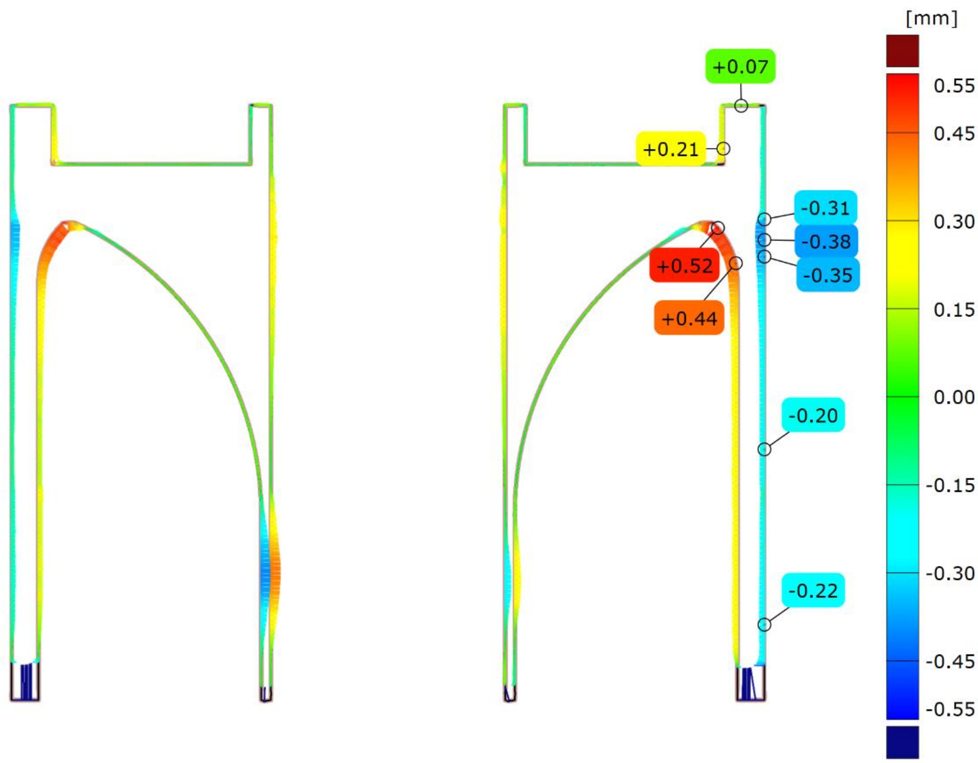


Figure 48, measured section

This operation is applied for each accurate analysis speed simulation and the simulation which better fits with deformed measured component is the simulation with 0.2mm element size.

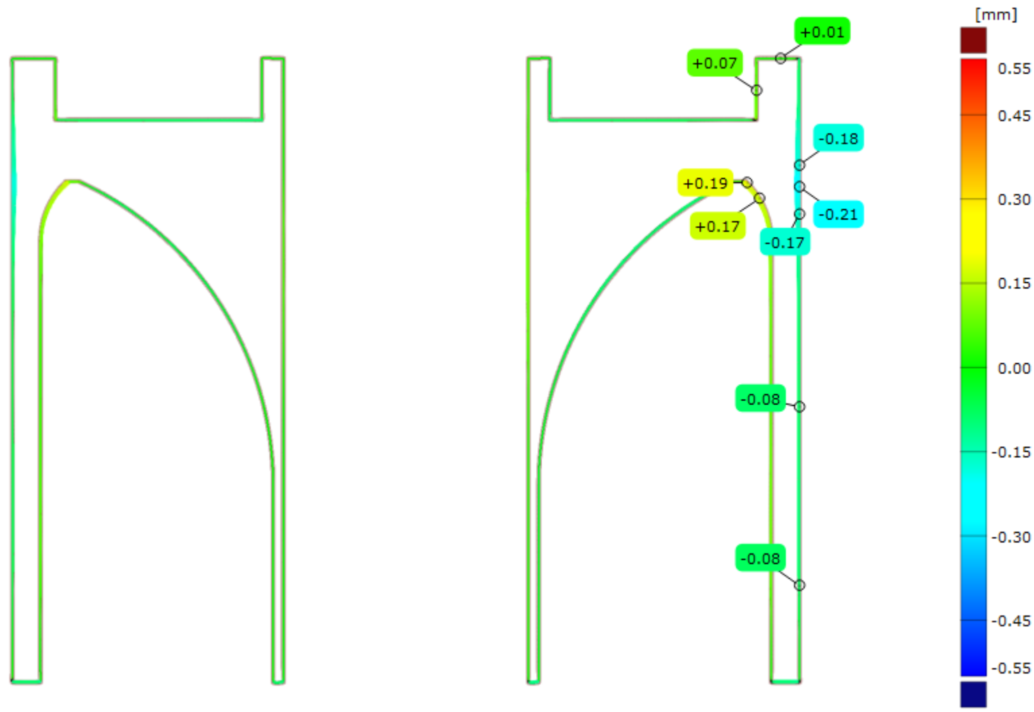


Figure 49, simulated 0.2mm accurate section

It is possible to observe that the qualitative trends correspond, but the magnitude is different. The simulation underestimates the deviation about 50%. It is correct to observe the time demanding of each simulation. The 0.2mm accurate analysis speed is the best one but is also the most time demanding. In the chart below it is possible to observe that all accurate analysis speed requires so much time more respect the equal element size of normal analysis speed.

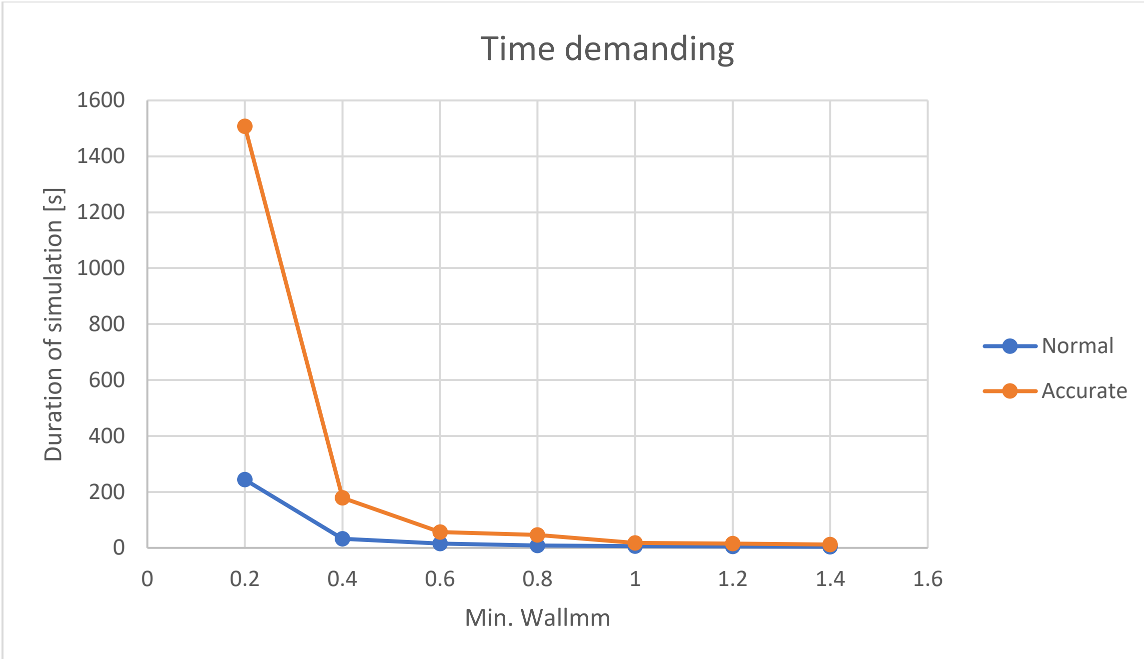


Chart 3, time demanding of simulation in function of analysis speed and element size

The compensation requires a bigger time demanding respect the simulation, because it had to re-iterate the process many times. So, the compensation of Canonical Model should require more than 3 days of calculate and considering the undervalue of 50%, the cost of each job, it is taking the decision to not print the compensation by simulation of Canonical Model.

5.2 Compensation by measurement

The first three steps of compensation by measurement workflow consist of to process the nominal geometry, scan the deformed geometry and polygonise it. These steps are already done. So, it is possible to generate the deviation file of deformed geometry respect nominal one. It is possible to continue with the application of inverse field to obtain the compensated geometry.

So, it is necessary to set compensation parameters. Three compensations are realized to understand the effect of build plate constraints. The compensations are compared respect Nominal Geometry and they are represented in below. Magnitude and reliability are the same for all compensations.

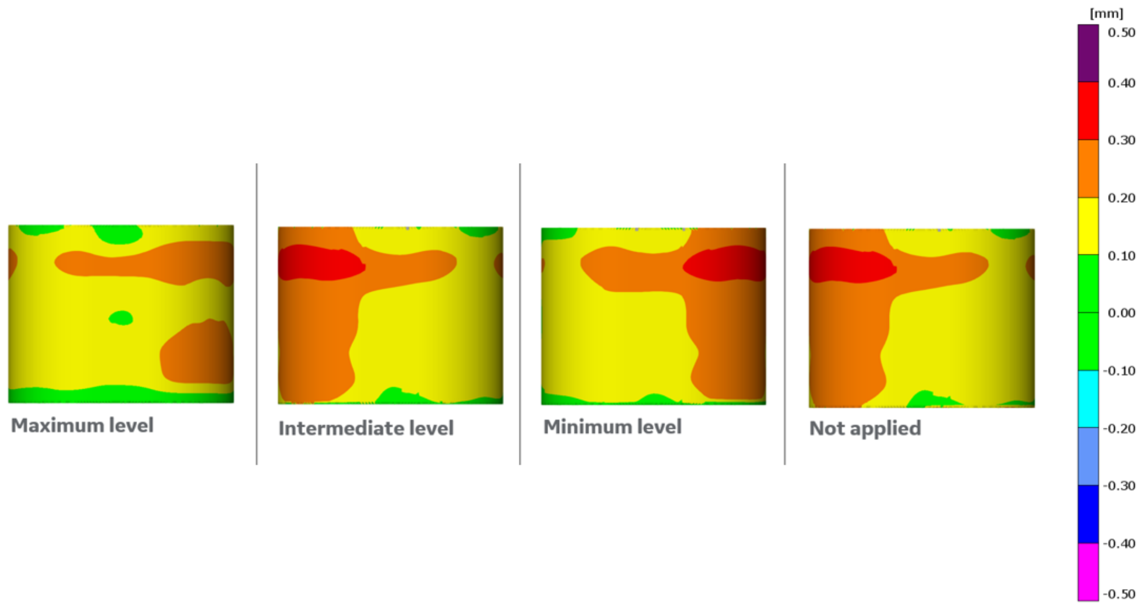


Figure 50, setting of build plate constraints compensation

The goal is to avoid the compensation of firsts layers, which are influenced by the stiffness of build plate. The maximum level gives the result desired.

It is possible to continue with the definition of volumes. It is necessary to define the volumes which circumscribes the local defects.

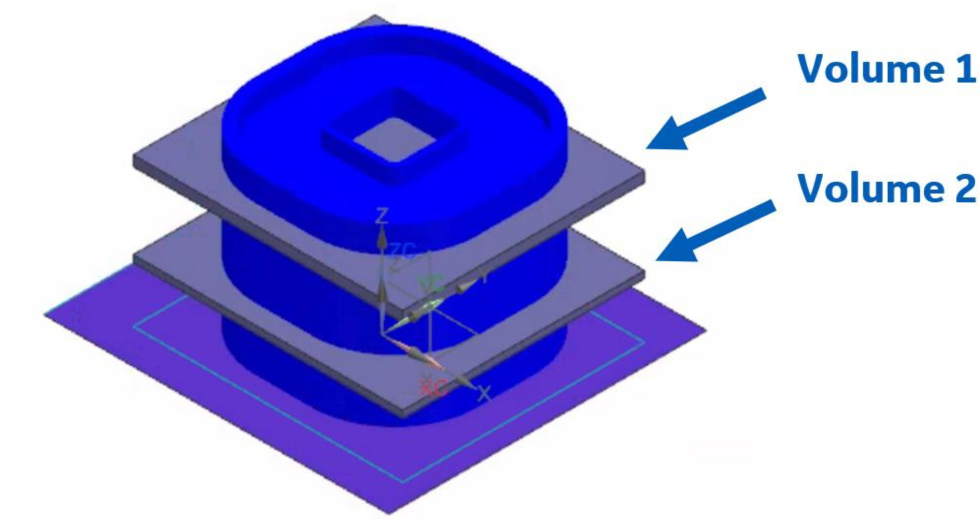


Figure 51, definition of volumes

In the table in below the magnitude and reliability of each volume are summarized.

	Magnitude	Reliability
Volume 1	0,7	10
Volume 2	0,7	10
General	0,7	5

Chart 4, magnitude and reliability of different volumes

The magnitude is chosen in function of experience and knowledge about compensation practice. The reliability is chosen in function of the geometrical detail of deformed geometry. So, in corresponding of local defects it is necessary to increase the reliability to generate a more accurate compensation.

The Compensated Geometry is represented in Figure 52.

Figure 52, compensated by measurement

The deviation of compensated geometry respects the nominal one is shown in below.

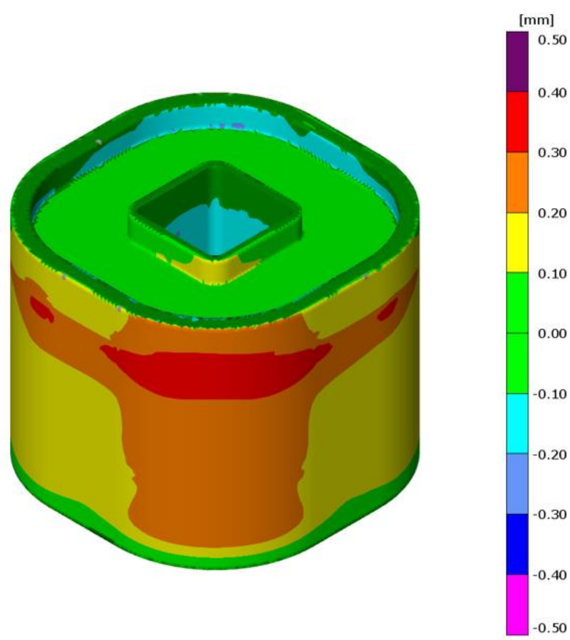


Figure 53, deviations of compensated geometry respect the nominal one

So, it is possible to process the compensated geometry. The material, the machine and process parameters used are equal for the nominal print.

5.2.1 Analysis of the results

The deviations of printed compensated geometry are calculated respect the nominal geometry, and they can be observed in below.

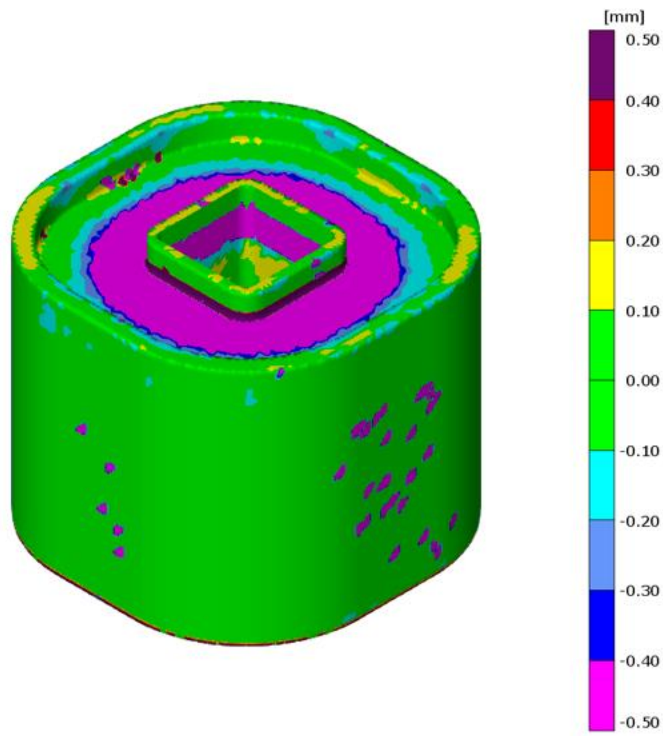


Figure 54, deviation map of compensated printed component

There is a global improvement of vertical surfaces, and it is clearly observable with the comparison of the two deviations comparison.

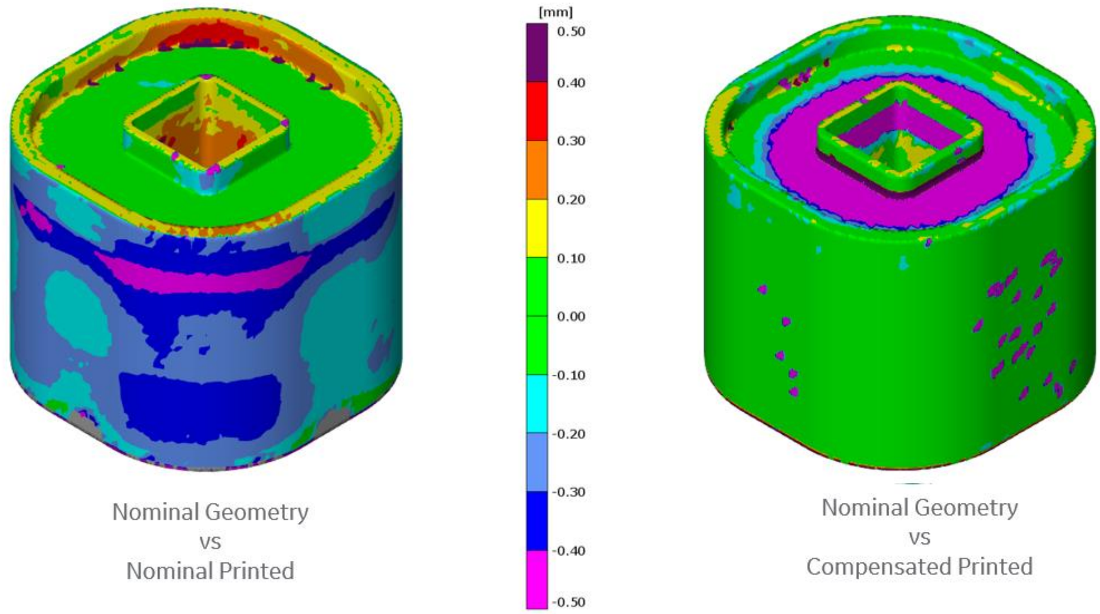


Figure 55, deviation map comparison

An initial comparison it is possible to observe that the green zone is increased, and the deviation are much smaller than before. It is useful to analyze the maximum deviation value before and after:

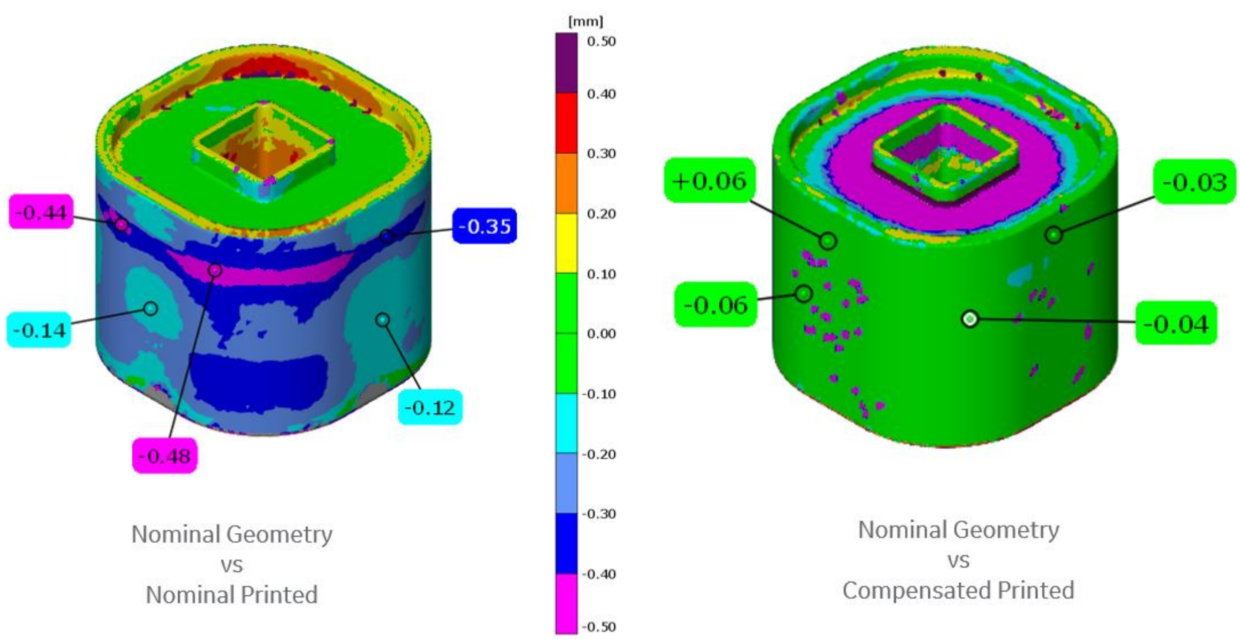


Figure 56, maximum deviation points comparison

The maximum values of deviation fell by an average of 65%. It is necessary to continue the analysis, considering more points on more sections.

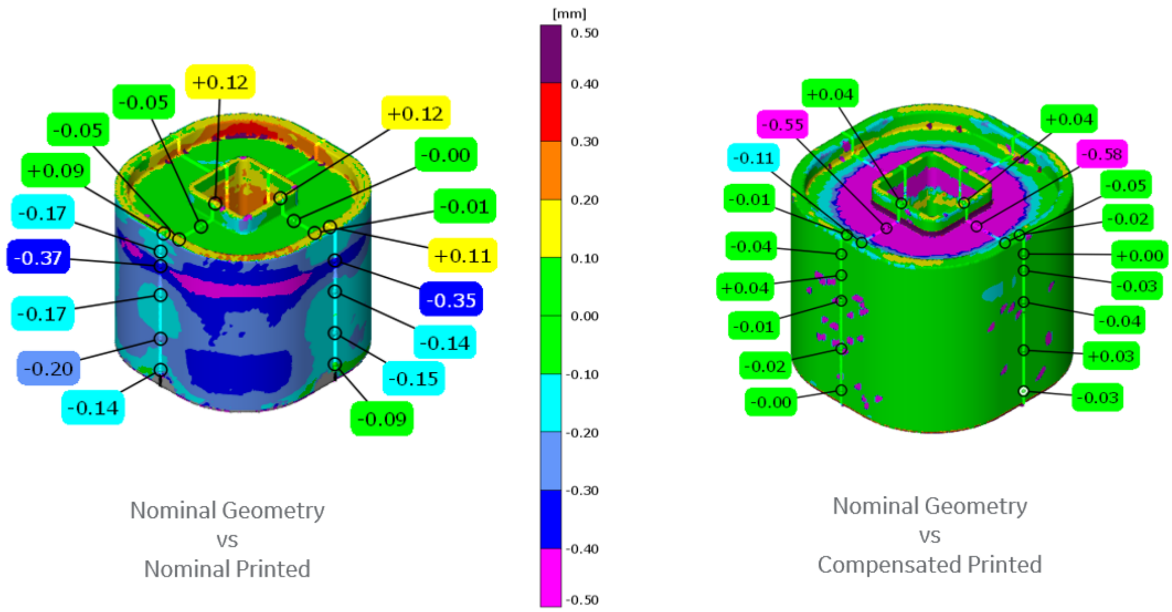


Figure 57, deviation sections comparison

If the bottom surface is ignored until the cause of huge deviation is associates to EDM cut, the global deviations have decreased by 60% on average.

It is possible to focus on local defect on Canonical Model, the line, as shown in Figure 58. After a fast view control, it is possible to understand that there still are build lines, as shown in below.

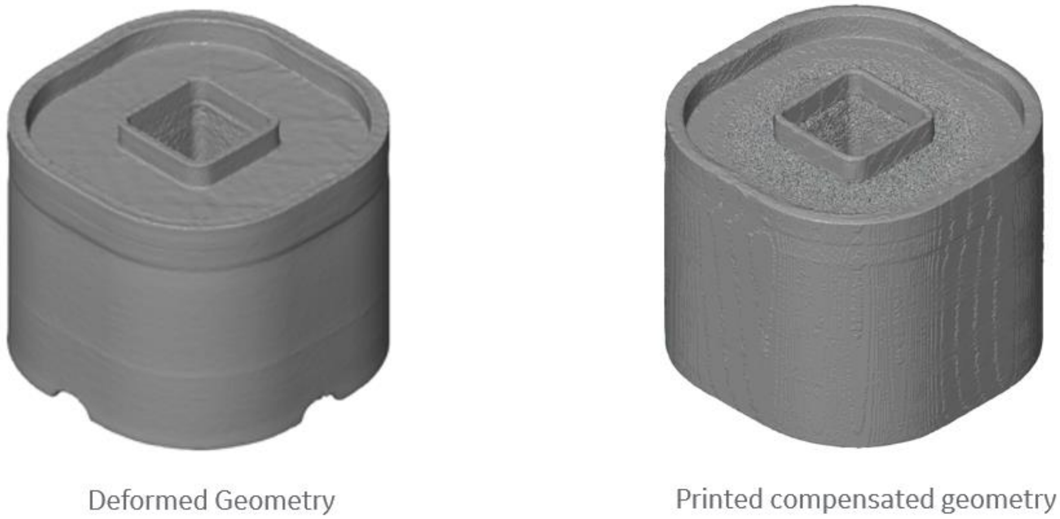


Figure 58, view comparison

To describe the build line before and after compensation procedure, two sections are considered, and the build line parameters are calculated.

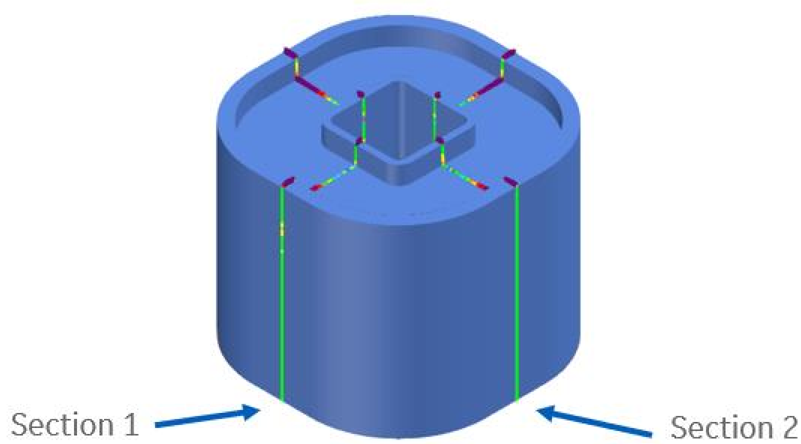


Figure 59, sections overview

The results from sections are comparable. So, only the section 1 is shown.

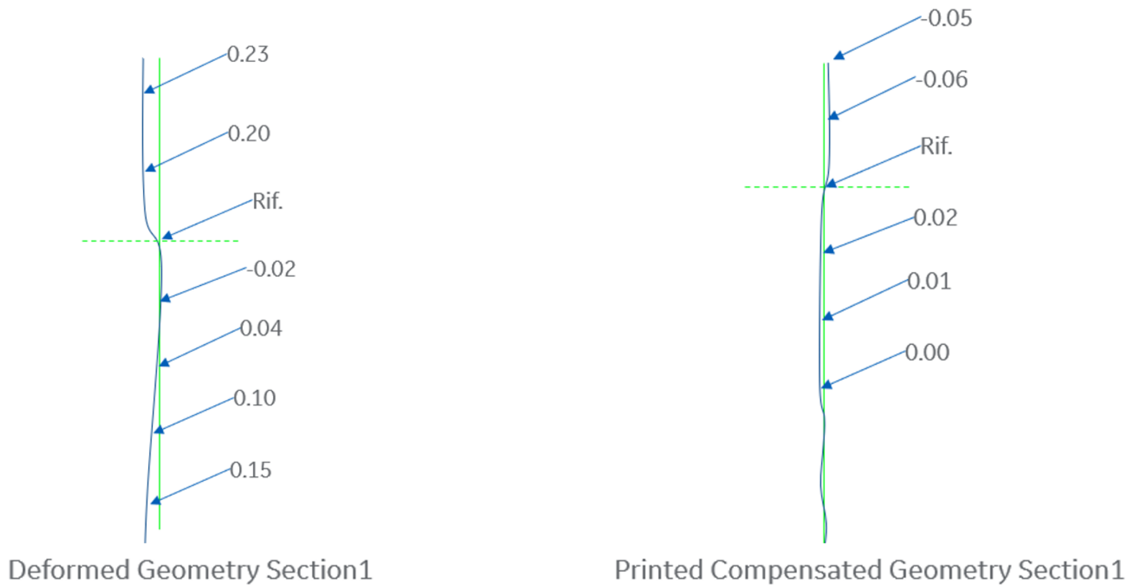


Figure 60, deviation section for build line comparison

First of all, it is clear that the build line moved on Z-axis. It moved up 1mm. Now it is possible to calculate the build line parameters.

The parameters calculated are condensed in the table in below.

Table 5, build line parameters of build line comparison

	Deformed Geometry	Printed Compensated Geom.
Δ^°	14°	2°
Sh [mm]	0.24	0.04
Mg [mm]	0.38	0.05

5.3 Conclusion

The compensation procedure for Canonical Model makes possible to say that:

- Compensation by simulation could be advantageous until it does not require a first job but, unfortunately, the simulation process tool is still not able to describe quantitatively the local defects; even if it is able to describe qualitatively them.
- Compensation by measurement procedure can improvement the global and local defects even if it is no able to avoid them. Indeed, in this case of study, even the build line is still visible, its magnitude is drastically decreased, and it does not influence the mechanical properties of the component.

Could be interesting to apply the Compensation by Simulation procedure and measure the improvements.

Chapter 6

Compensation of Power Gear Box

The Power Gear Box, or PGB, is a component typically produced by traditional manufacturing technics. The multiple advantages of additive manufacturing, and in particular L-PBF, create an interest to produce the PGB by this innovative technology.

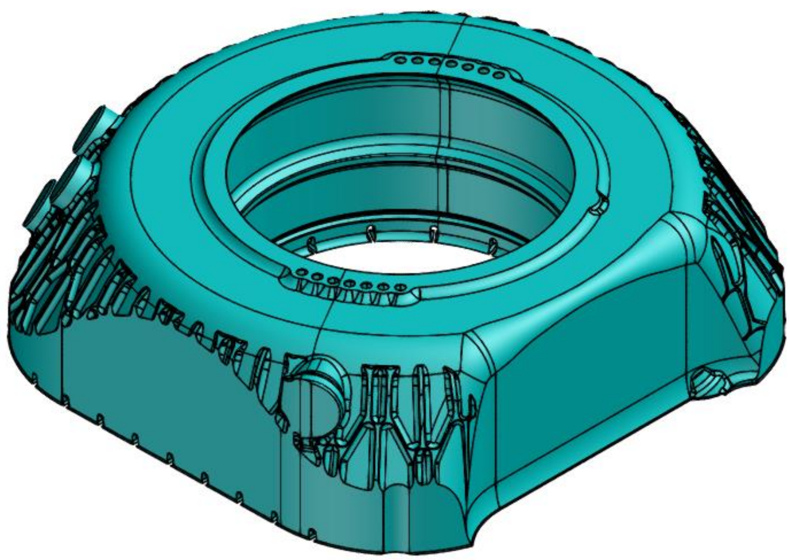


Figure 61, nominal PGB geometry

The Nominal PGB Geometry was already printed, and the Deformed component was scanned. Unfortunately, the component presents few defects. There is a general deformation due to volumetric withdrawals, and there are two local defects: two build lines. It is possible to observe the local stairs in the Figure 65.

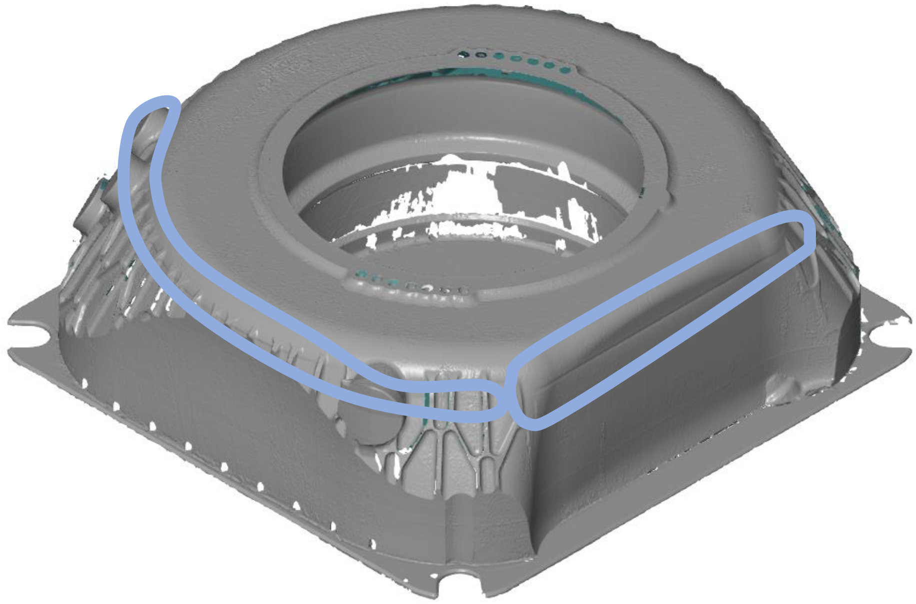


Figure 62, local defects on processed PGB

In the following imagine is possible to see the deviation of Measured Component respect the Nominal Geometry.

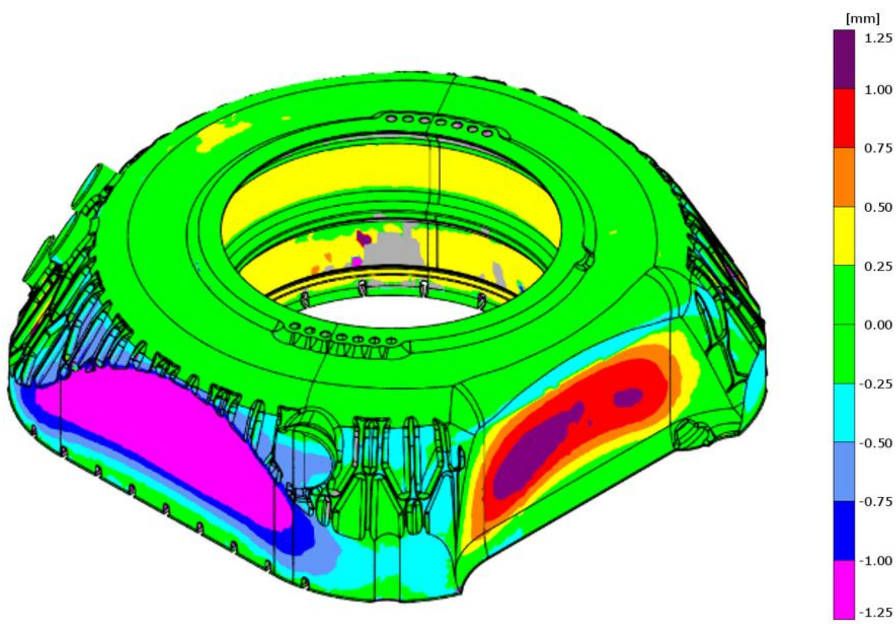


Figure 63, deviation of processed PGB

These defects require additional mechanical treatments. So, it is useful to avoid, at list to reduce, them by compensation.

6.1 Compensation by Simulation

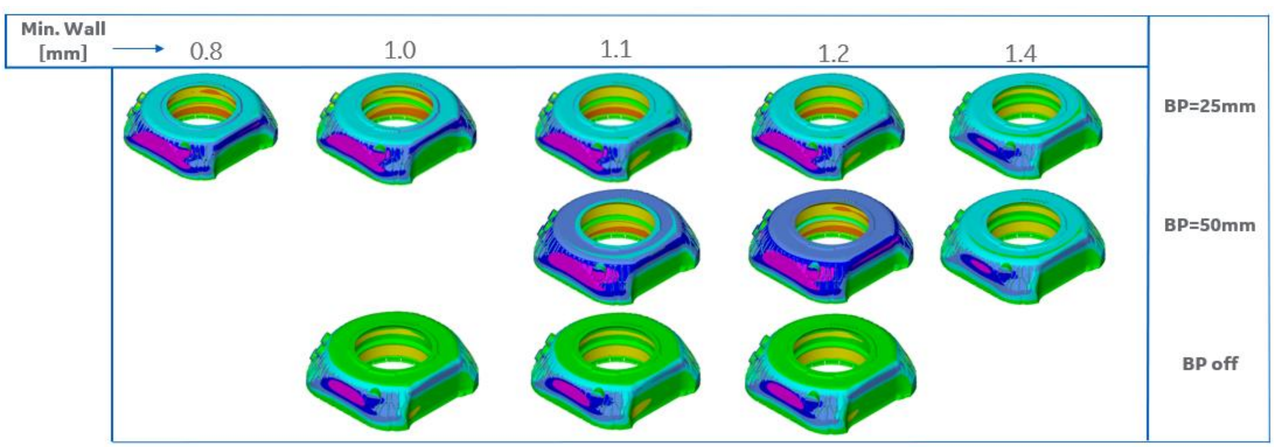
To run the simulation is necessary to prepare:

- Nominal Geometry STL
- Process parameters file
- Simulation parameters

The first and second files are easily prepared because it is not an active-mind action in this case. The operator had to digit all process parameters used to process the nominal geometry. The third file require more accuracy, because there is no evidence to know the optimal simulation parameter set.

Until the nominal geometry is already processed, it is possible to run many simulations with different parameters and compare them with the measured to detect the optimal one. I realized XX simulations, which have different element size, build plate stiffness and analysis speed. In the following table all deviation of simulated respect the nominal geometry are represented.

Table 6, resume of PGB process simulations



The simulation which best fits with Measured is the one with 1.1mm element size, with analysis speed accurate and build plate stiffness function deactivated.

Unfortunately, the deviations of Simulated deformed component are 50% undervalue of the real Deformed component. So, considering the cost of the job, the compensated PGB obtained by compensation by simulation is not printed.

6.2 Compensation by Measurement

Until the Nominal geometry was already processed, and the result was scanned, polygonised, so it is possible to generate the deviation file of deformed geometry respect nominal one. It is possible to continue with the application of inverse field to obtain the compensated geometry.

So, it is necessary to set compensation parameters. To understand the effect of build plate constraints, three compensations are realized. The compensations are compared respect Nominal Geometry and they are represented in below. Magnitude and reliability are the same for all compensations.

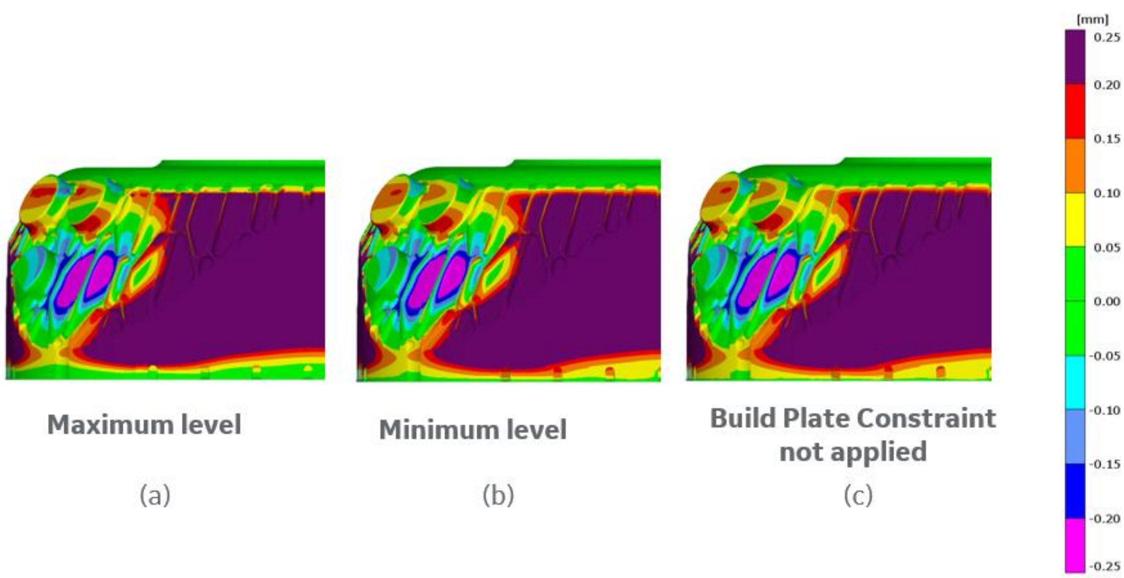


Figure 64, setting of build plate constraints compensation

The goal is to avoid the compensation of firsts layers, which are influenced by the stiffness of build plate. The maximum level gives the result desired.

It is possible to continue with the definition of volumes. It is necessary to define the volumes which circumscribe the local defects.

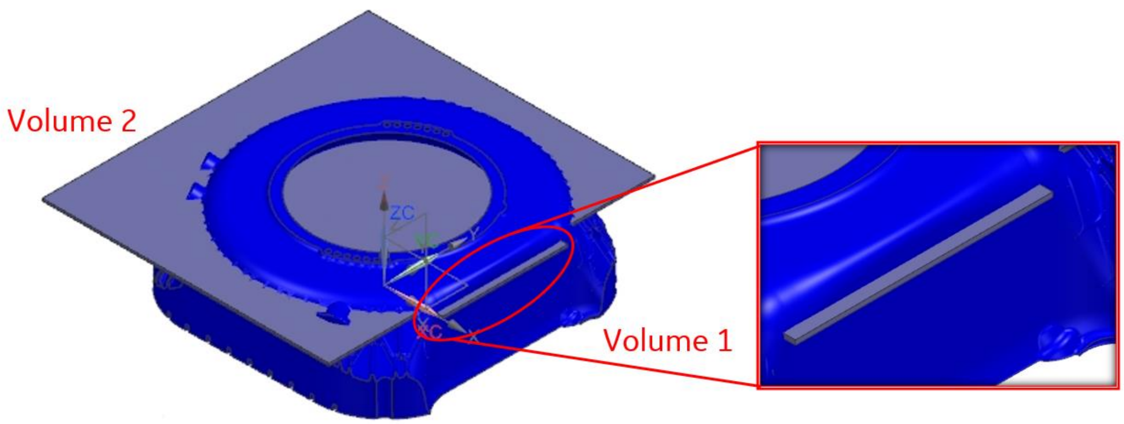


Figure 65, PGB volumes definitions

In the table in below the magnitude and reliability of each volume are summarized.

Table 7, resume of compensation parameters of PGB

	Magnitude	Reliability
Volume 1	0,7	10
Volume 2	0,7	10
General	0,7	6

The magnitude is chosen in function of experience and knowledge about compensation practice. The reliability is chosen in function of the geometrical detail of deformed geometry. So, in corresponding of local defects it is necessary to increase the reliability to generate a more accurate compensation.

The Compensated Geometry is represented in Figure 69.

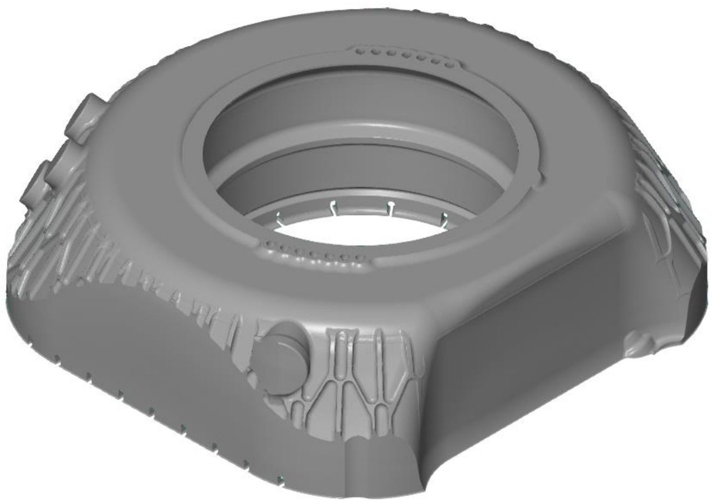


Figure 66, PGB compensated by measurement

The deviation of compensated geometry respects the nominal one is shown in below.

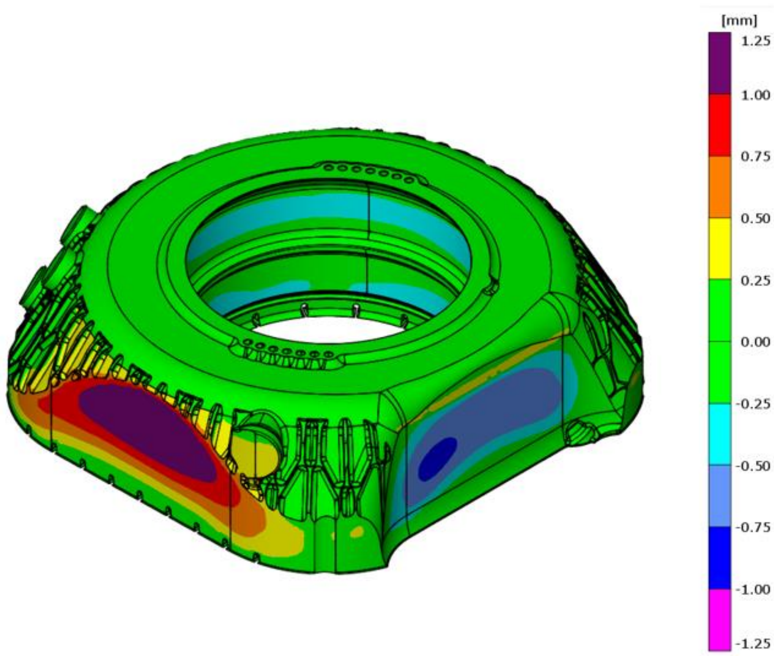


Figure 67, PGB compensated deviation map

Until the compensated geometry is completed, it is possible to print it.

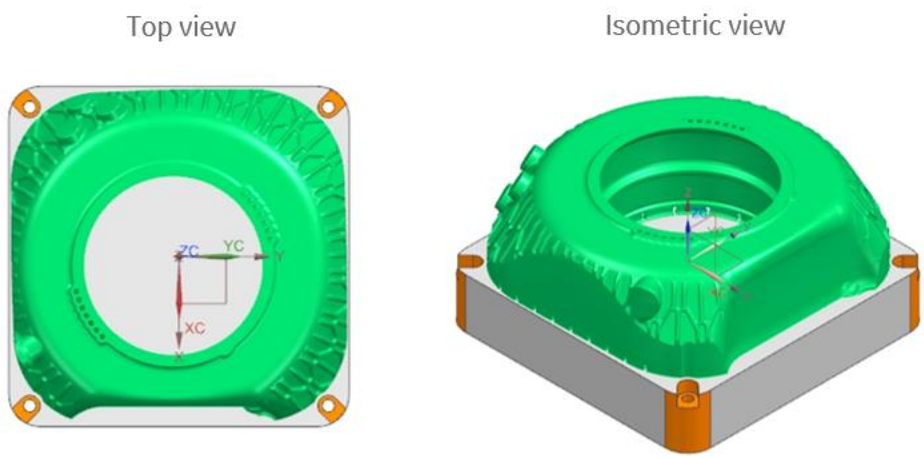


Figure 68, build preparation of PGB compensated

The printed compensated component is scanned and polygonised.

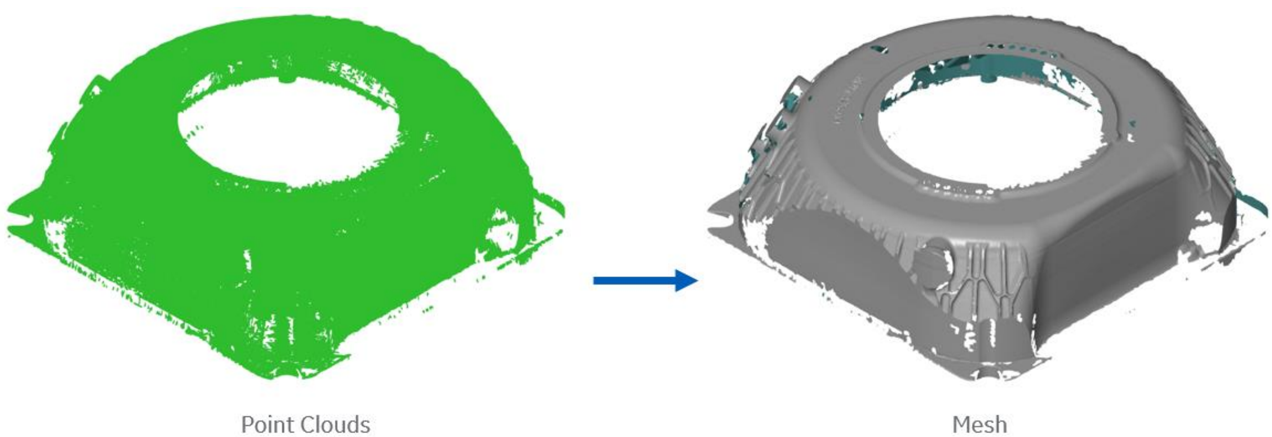


Figure 69, point clouds and mesh of printed compensated PGB

6.2.1 Analysis of the results

The deviations of printed compensated geometry are calculated respect the nominal geometry, and they can be observed in below.

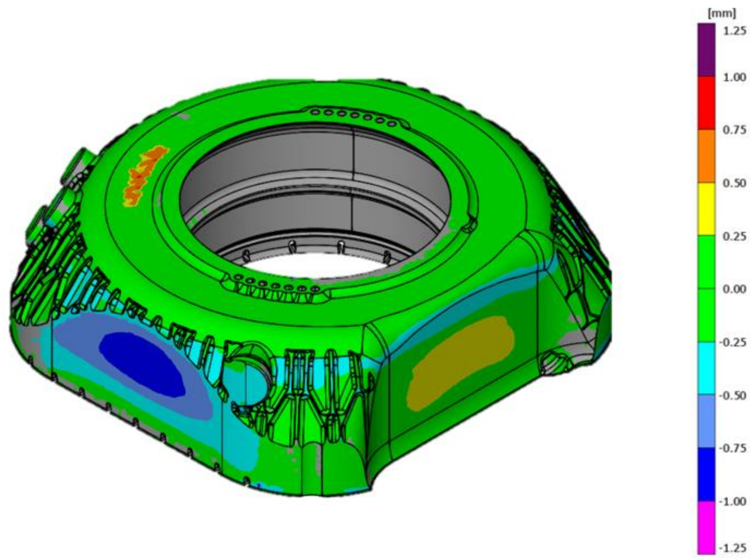


Figure 70, deviation map of printed compensated PGB

There is a global improvement, and it is clearly observable with the comparison of the two deviations comparison:

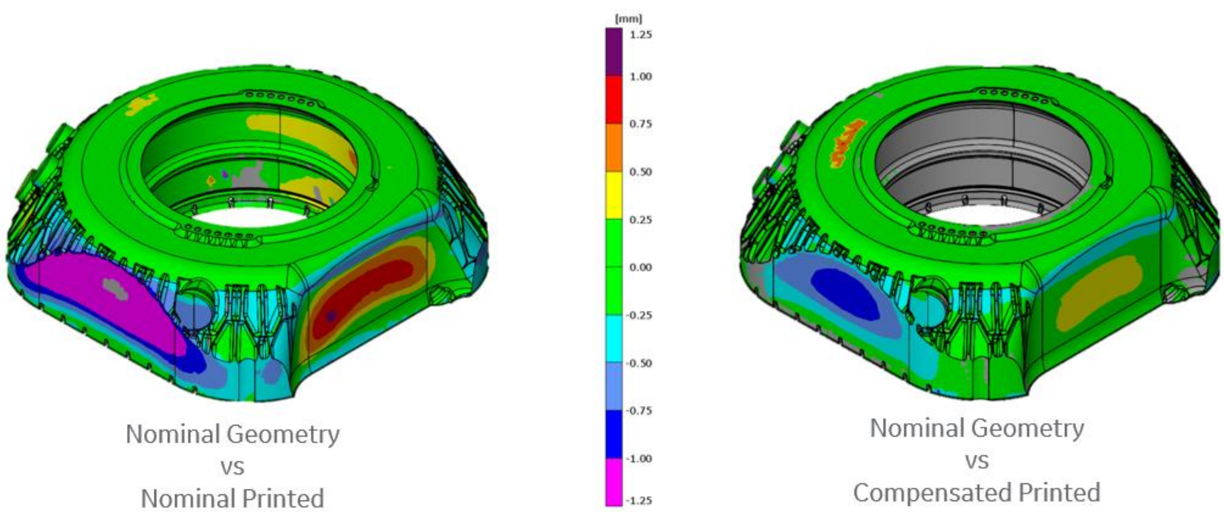


Figure 71, deviation map comparison

An initial comparison it is possible to observe that the green zone is increased, and the deviation are much smaller than before. It is useful to analyze the maximum deviation value before and after:

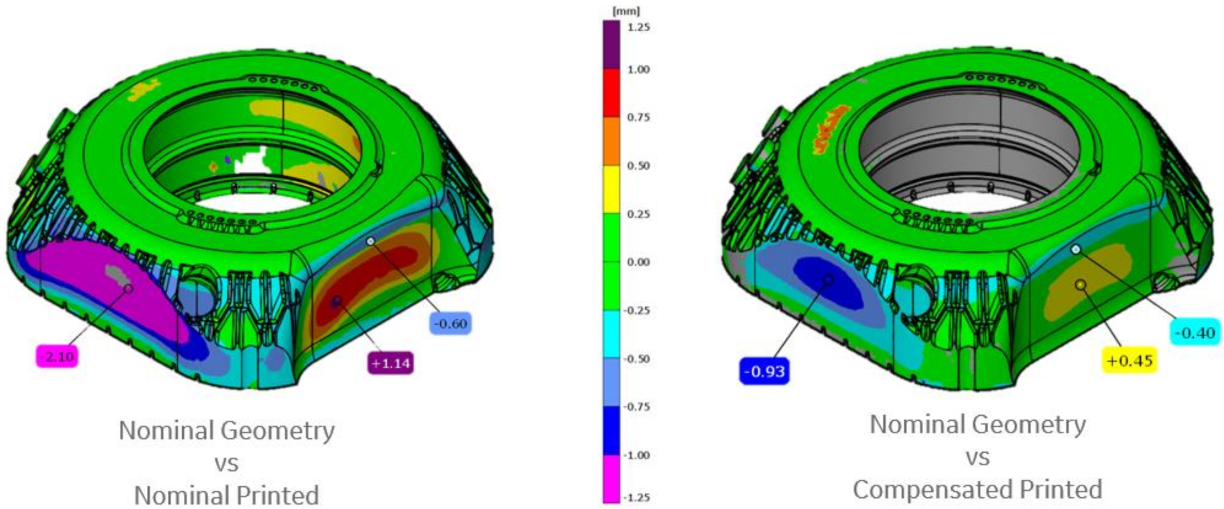


Figure 72, max deviation points comparison

The maximum values of deviation fell by an average of 55%. It is necessary to continue the analysis, considering more points on more sections.

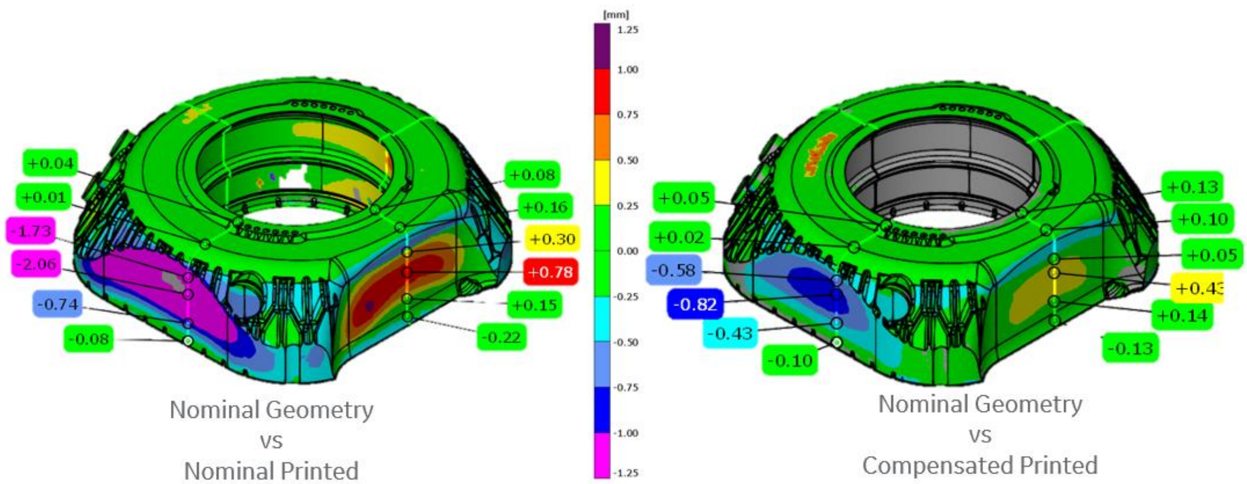


Figure 73, deviation sections comparison

The global deviations have decreased by 50% on average.

It is possible to focus on local defects of PGB, the two build lines, as shown in Figure 77. After a fast view control, it is possible to understand that there still are build lines, as shown in below.

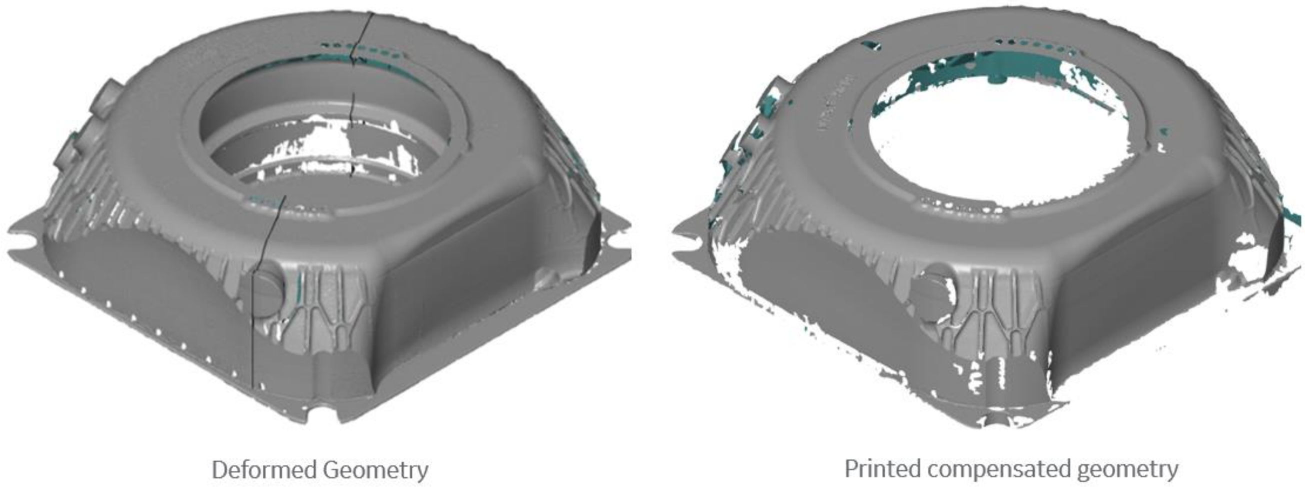


Figure 74, view comparison

But let’s analyze build line by one. The build line 1 has the biggest impact and there is a visual improvement.

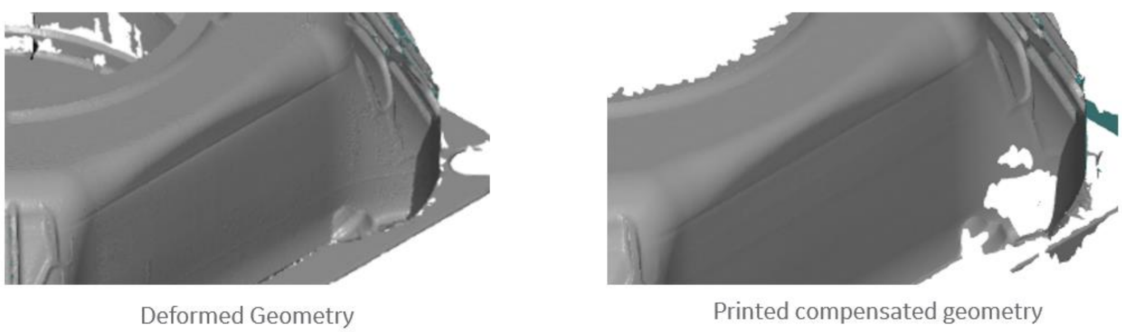


Figure 75, view comparison of build line 1

To describe the build line before and after compensation procedure, there are considered three sections and for each one there are calculate the build line parameters.

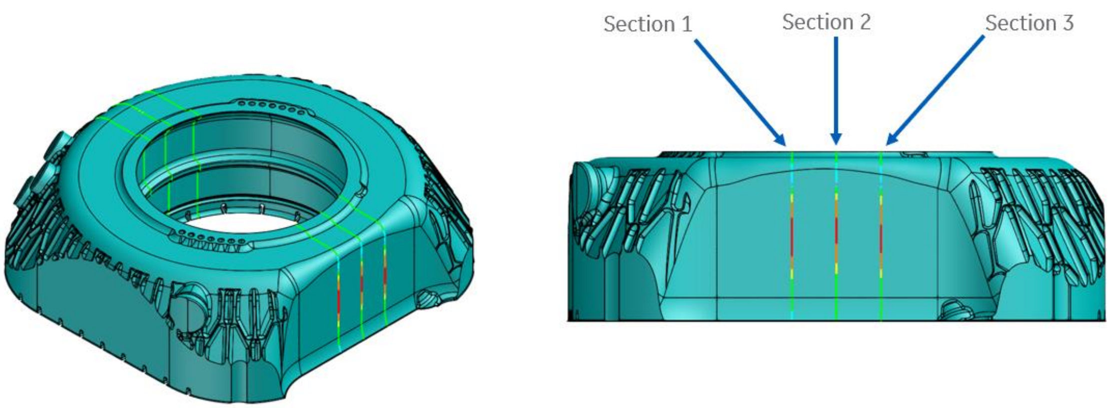


Figure 76, section for build line 1 overview

The results from sections are comparable. So, only the section 1 is shown.

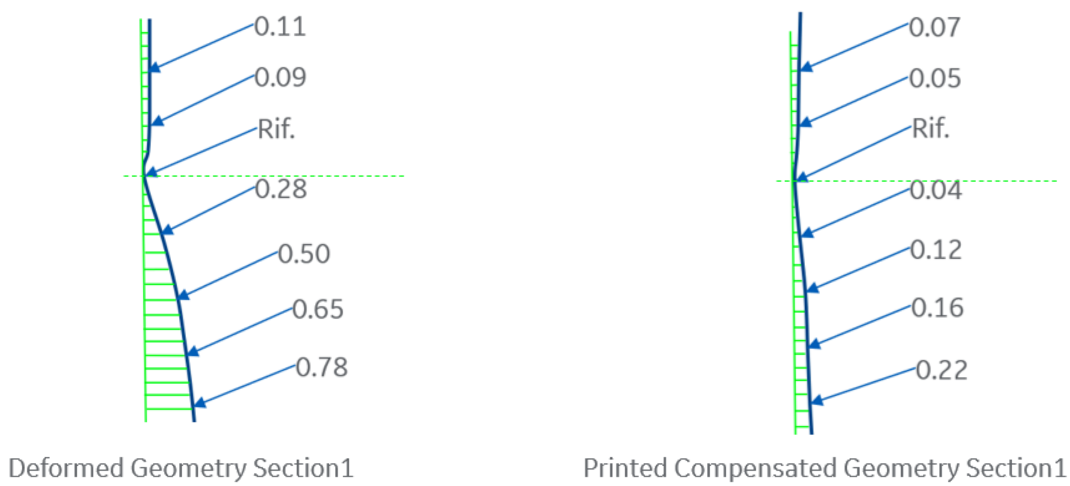


Figure 77, deviation section for build line 1 comparison

The parameters calculated are condensed in the table in below.

Table 8, build line parameters of build line 1 comparison

	Deformed Geometry			Printed Compensated Geom.		
	Sec. 1	Sec.2	Sec. 3	Sec. 1	Sec.2	Sec. 3
Δ^°	21°	22°	21°	9°	9°	8°
Sh [mm]	0.37	0.39	0.37	0.09	0.15	0.14
Mg [mm]	0.87	0.93	0.87	0.27	0.33	0.32

Until the values of different sections are comparable, it is useful to calculate the average of sections and condensate.

Table 9, average of build line 1 parameters comparison

	Def. Geom. Average	Printed Comp. Geom. Average
Δ^°	21°	9°
Sh [mm]	0.38	0.13
Mg [mm]	0.89	0.31

The build line 2 is analyzed as done for build line 1. In this case too, the build line 2 is still present, even the compensation procedure applied.

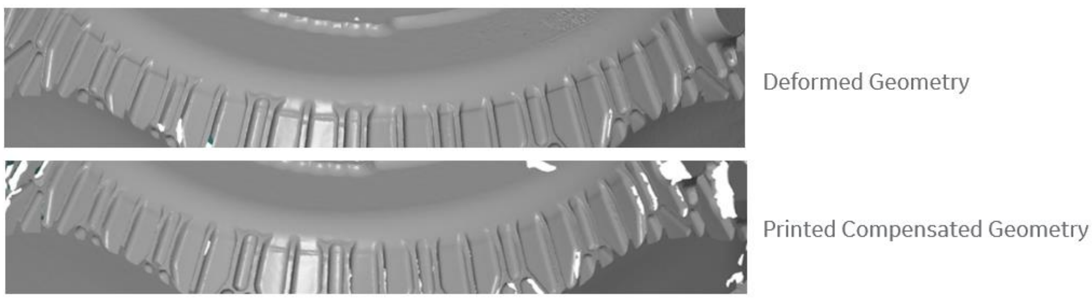


Figure 78, view comparison of build line 2

To describe the compensation effects, there are considered three sections and for each one there are calculate the build line parameters.

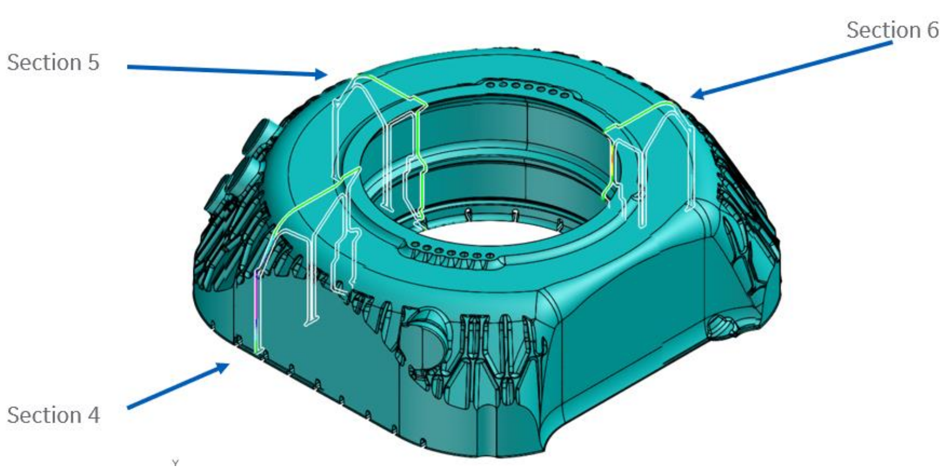


Figure 79, section for build line 2 overview

The results from sections are comparable. So, only the section 4 is shown.

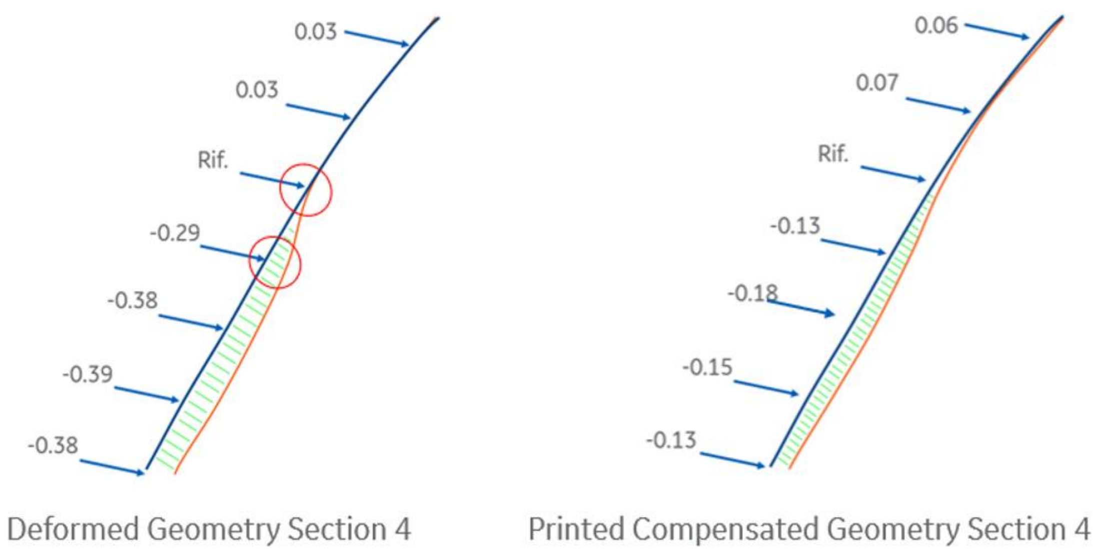


Figure 80, deviation section for build line 2 comparison

The parameters calculated are condensed in the table in below. The analysis of delta inclination values shows that there are two build line center, and they are red circled in Figure 83. So, there are calculated the parameters for each build line, A and B.

Table 10, build line 2 parameters comparison

		Deformed Geometry			Printed Compensated Geom.		
		Sec. 4	Sec.5	Sec. 6	Sec. 4	Sec.5	Sec. 6
A	Δ^°	14°	15°	12°	3.5°	7°	2°
B	Δ^°	11°	14°	16°	4.5°	1°	4°
A	Sh [mm]	0.26	0.28	0.22	0.06	0.12	0.03
B	Sh [mm]	0.38	0.45	0.34	0.18	0.19	0.1
A	Mg [mm]	0.36	0.41	0.22	0.07	0.23	0.03
B	Mg [mm]	0.36	0.41	0.22	0.07	0.23	0.03

Until the values of different sections are comparable, it is useful to calculate the average of sections and condensate.

Table 11, average of build line 2 parameters comparison

		Def. Geom. Average	Printed Comp. Geom. Average
A	Δ^°	14°	4°
B	Δ^°	14°	3°
A	Sh [mm]	0.25	0.07
B	Sh [mm]	0.39	0.16
A	Mg [mm]	0.33	0.11
B	Mg [mm]	0.33	0.11

6.3 Conclusion

The compensation procedure for PGB makes possible to say that:

- Compensation by measurement procedure can improvement the global and local defects even if it is no able to avoid them.
- Compensation by simulation could be advantageous until it does not require a first job but, unfortunately, the simulation process tool is still not able to describe quantitatively the local defects; even if it is able to describe qualitatively them.

Could be interesting to apply a second iteration of Compensation and observe how much the improvements will be. But had to be clear that each iteration requires a job. So, a compromise between pain and gain had to be research.

Conclusions

Additive Manufacturing changed many aspects of engineering, and I am confident to say that it will change many mores. New geometries, new material, new way to concept products, new ways to concept production, prototyping.

In now time many aspects had to be improved and many defects must be avoided. Geometrical defect due to temperature gradients is one of them. Compensation is a pragmatic way to resolve this problem.

Compensation by Simulation and Compensation by Measurement shown different advantages and disadvantages. Both had to exist and had to be developed. The actual results are encouraging. It is possible to obtain an objective improvement trough compensation procedure. Probably it will be hard to totally avoid defects, but they can be reduced to the point that they are not significant for engineering aspects.

There are many possible next steps. Simulation process tool requires to be developed, the potential is high, it can be a game-changer. Must be studied the results of multiple iteration of compensation: a single application of compensation gives a consistent result; multiple iteration can increase the improvement? How much? The development of affiliate technologies, for example laser scanner technologies, will improve the procedure.

At the end of my Master’s thesis work It is possible to affirm that Compensation procedure reduces distortions defects, its potential is high and must be developed.

Table of figures

Table of tables

Table of charts

Acronyms

AM	*Additive Manufacturing*
ASTM	*American Society of Testing and Materials*
BAAM	*Big Area Additive Manufacturing*
CAD	*Computer Aided Design*
CAM	*Computer Aided Manufacturing*
CT	*Computed Tomography*
DED	*Direct Energy Deposition*
DFA	*Design for Assembly*
DFAM	*Design for Additive Manufacturing*
DFM	*Design for Manufacturing*
DMLM	*Direct Metal Laser Melting*
EBM	*Electron Beam Melting*
EDM	*Electrical Discharge Machining*
FDM	*Fused Deposition Modeling*
FEM	*Finite Element Method*
FE	*Finite Element*
FO	*Focus Offset*
FVM	*Finite Volume Method*
HIP	*Hot Isostatic Pressure*
LO	*Line Offset*

LPT	*Low-Pressure Turbine*
NURBS	*Non-Uniform Rational Basis Spline*
PBF	*Powder Bed Fusion*
RP	*Rapid Prototyping*
SL	*Stereolithography*
SLM	*Selective Laser Melting*
SLS	*Selective Laser Sintering*
STL	*STereoLithography or Standard Triangulation Language*
TO	*Topology Optimization*
UV	*Ultraviolet*

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