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Material and process characterization for coupling topological optimization to additive manufacturing

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ABSTRACT

In Additive Manufacturing (AM), a main material and a support material can be required to manufacture a model. The support material sometimes remains inside the prototyped model and is difficult to clean. Removing the support material results in a waste of time, material and money, which goes against the principles of Ecodesign, especially when the support has no structural function.

This research work presents how a topological optimization can be applied on a part produced by rapid prototyping. Numerical simulation was used to optimize the inside structure and the mechanical strength was assessed to optimize the topology. This resulted in design solutions that support the use context with different functions. We more particularly worked on the correlation between the virtual and mechanical results to check the information. The Design for Manufacturing approach was used through different mechanical tests requiring the implementation of data through numerical simulation. The manufacturing characteristics were integrated into the mechanical analysis. The study proposes an alternative geometry through a design for manufacturing approach and a topological optimization applied to additive manufacturing.

KEYWORDS
Additive manufacturing; rapid prototyping; numerical optimization; multi jet modeling

1. Introduction

AM is nowadays widely used in industrial product development to realize prototypes, functional models or other applications. The main advantage of AM is the ability to create almost any possible shape, thanks to the layer-by-layer building principle which is specific to all AM technologies. This capacity is led by the layer-by-layer building like all AM technologies. Several AM-based technologies [27]: Vat photo-polymerization, Material jetting, Binder jetting, Powder bed fusion, Material extrusion, Directed energy deposition and Sheet lamination (AM process category in accordance with ISO CD/17296-2) Researchers mainly work on the influence of part orientation, slicing strategy, matching internal patterns to improve cost, product quality, built time, etc. Numerical topological optimization is a disruptive technology which allows the modeling of really innovative shapes, based on trade knowledge [25]. The union of the two technologies, AM and numerical topological optimization, seems to be very promising, more particularly for steel machining (for a real ROI on the mass gain).

Since the appearance of rapid prototyping, different technologies have emerged. The manufacturing by layers gets a common characteristic and additive manufacturing or 3D printing make it possible to use various materials. To manufacture parts with complex geometries a support material is required that will hold the external and internal surfaces in position. In most cases, the support material is cleaned during the finishing or confined into the model. The consumable cost is often expensive as the support material is lost after completion for cleaning. Moreover, the resin used generally has a negative environmental impact

The topology structure of the main material used to manufacture a part has evolved over the last few years to better support the geometry. The use and the physical constraints are not taken into account when numerically generating the structure. Numerical simulation offers a lot of advantages with the optimization to present an adaptive model integrating those constraints.

This research work presents two issues:

- The internal structure adaptation of a model in order to include constraints in rapid manufacturing.
- The weight gain to reduce the material volume and remove the difficulties during the finishing.

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Main objectives are defined according to a research approach applied to additive manufacturing, using a specific machine. We present the results with respect to a control which is used to compare additional information. First of all, we present a state of the art of the technologies and research approach used before proceeding to our proposition. After the analysis of our results, we will present a case study based on an injection mold.

2. State of the art

2.1. Technology part

We use different tools to produce the parts and optimize their internal structures:

- The Multi-Jet Modeling which has the same approach as the inkjet but with a photosensitive resin. A post-treatment is often used to remove the support material [27].
- The stereo-3D image correlation based on the principle of photogrammetry. A calculation method of spatial intersection [2] allows us to realize a 3D reconstruction of the object. The displacement measurement point is achieved by tracking.
- The numerical shape optimization of a model. We know three great categories of shape optimization in mechanical structures like: "the parametric optimization", the "geometric optimization" and the "topological optimization" [4].

This third category of optimization is an appropriate method for the design step of new parts because it permits to develop concepts and to find solutions in the using area.

2.2. DFM part

The DFM approach [28] is used trough different mechanical tests in order to integrate the requirements data in the numerical analysis as soon as possible. Several manufacturing characteristics were integrated to interpret the mechanical behavior of the structure, such as layer-by-layer manufacturing, new materials (wood, bio materials) and new 3D printing techniques (complementary manufacturing systems) [12] [13]. The study presents an alternative geometry about existing structures through numerical simulation, mainly the numerical optimization linked to the Design For Manufacturing.

2.3. Optimization part

Optimization in additive manufacturing [8] is generally used in the context of the optimization of the build direction [18], parameter optimization trades, and optimization construction layers algorithm and so on. The optimization of the quantity of material used is an important goal. This optimization can match both the product material but also the support material. Figure 1 shows a topology optimization on both the part and the support used (two optimizations are performed separately. Optimization in the "design" zone is the area that can be optimized, the "non-design" zone cannot be changed).

AM machines generally offer the possibility of reducing the mass by using honeycomb shapes, lattices, etc generated by algorithms . . . The latter model the simplified form without taking into account the specifications of mechanical strength. They are usually applied to save internal matter.

There already exist many researches on the influence of cellular structures. Reference [26] studies the influence

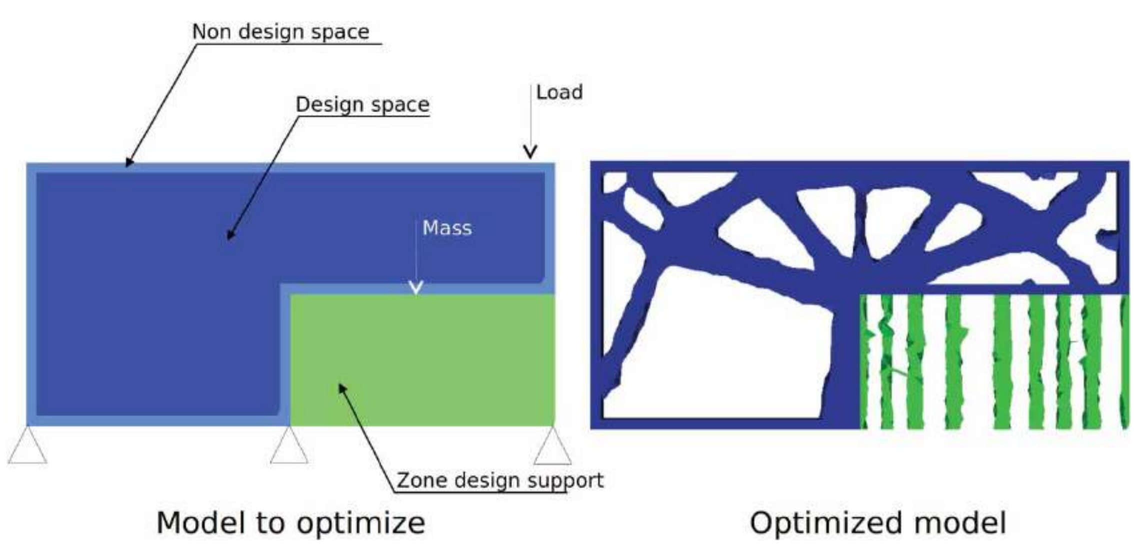


Figure 1. Simple example of part and support optimization.

of circular and rectangular shapes on the polyamide through compression tests. The study shows the influence of two types of geometric shapes based on their uses. A circular structure can absorb 43.5% more energy than a rectangular structure that behaves better still at high deformation rates (useful for quick dynamics like crash, explosions . . .). Paper [24] investigates the use of lattice structures including rapid prototyping to lighten sandwich panels while maintaining their mechanical strength. The study enabled to determine that the directions of the anisotropy of the lattice influences the mechanical behavior of the entire panel used. The lattice modeling can be adjusted according to the specifications of mechanical strength. Other studies develop specific structures like curved [8], honeycomb [3] or cell shapes, "tetrachirales" [17] or "hexachirales" [19]. However, these studies do not integrate the notion of mechanical strength to optimize the best shape. The topological optimization through numerical simulation can solve this problem. Paper [21] shows the interest to integrate the topological optimization but also to highlight some difficulties such as:

- The difficulty to manage the drainage system of the support part
- The size of the CAD file and the implementation difficulty

Existing researches mainly focus on the implementation of new forms (like honeycomb lattices) but do not uses topology optimization to a full extend. Knowledge management is however necessary to obtain innovative forms in the trade context. It is important to note the necessity to manage the drainage system of the support part. Authors in [20] develop a recent methodology which allows the production of a topological optimized part by low cost FDM. This methodology uses the classic optimization process to optimize the mass of the part (including the skin of the part).

The difficulty of the integration of topological optimization in additive manufacturing is to correctly characterize the material behavior and the process limits.

3. Proposition

Our approach proposal is to integrate, the knowledge Based System (paragraph 3.1) into a CAD model from physical testing (paragraph 3.1), experimental design (paragraph 4) but also stresses induced by the forming processes or implementation (paragraph 5).

All these criteria are then implemented in a dedicated software for the integration of topological optimization in a CAD file. Figure 1 pictures our methodology.

3.1. Topological optimization

The Topology optimization problem can be defined as the search for the best allocation or distribution of material in a given design space [6]. The reference domain Ω ($\Omega \in \mathbb{R}^3$) is determined by the design space, boundary conditions and loads. Ω is also chosen due to the maximal space available. The aim is to find the best distribution of material *i.e.* to determine the subdomain ω of Ω filled with the material. From a mathematical point of view, a topological optimization problem can be written as pictured in equation 1. We seek to minimize the objective function f within certain constraints to define χ.

$$\min_{\omega \complement \Omega} f(\omega) : [C] \rightarrow \omega \in \chi \tag{1}$$

In practice the objective function may be represented by the weight, volume, the deformation energy . . . and the design variables by the dimensions (like thickness), the type of material, the mass, the frequencies and so on.

A topology optimization problem relative to an AM process can be defined by:

- Design spaces: a design space corresponds to the interior of the objects and a non-design space corresponds to the skin of the object (or any other area that should not be modified such as the apertures for cleaning). These areas are identified in CAD model.
- Design variables: it is the set of parameters of the design space related to the AM process to define the initialization problem of topological optimization. It includes the penalization factor, the pattern repetition and so on.
- Responses: responses correspond to structural responses, calculated in a finite element analysis, or the combinations of these responses to be used as objective and constraint functions in a structural optimization. Available responses could be for example static displacement, mass, volume, temperature, natural frequency, . . .
- Constraints : Constraints are based on responses by marking them with specific values
- Objective: The objective function is, as mentioned before, the minimization (or the maximization) of the problem, here a specific response (for instance the aim is to manage one response by objective function).

A Knowledge Based System (KBS) was developed to manage the AM process and material characterization for the topological optimization integration [11]. The KBS uses production rules and constraints to represent the declarative knowledge. It is the most usual representation of the heuristic know-how model. We were particularly interested in the scenario model [10] i.e. the decomposition of a problem in a series of tasks [1]. We based ourselves on the fact that each time an expert resolves a problem, he runs a scenario in an intuitive way. Schank [23] set up this structure by affirming that there are thousands of scenarios in the human memory. The different scenarios have been collected by tracking the work of experts based on a specific ontology [16].

Our structure is made up of a knowledge base including:

- A base of scenarios: experts translate the stages of their topological optimization and AM process into diagrams of sequences of tasks. They consequently use a scenario of optimization and AM process.
- A base of rules: it contains the production rules and uses the base of constraints for this purpose. These rules are associative, which means that each formalized rule must contain both the context of application of the rule and the condition of the processing of the rule. The rules are rules of production like "If" (Conditions), and "Then" (Conclusions). The "Conditions" part is the process of the rules and the "Conclusions" part describes the actions to be started in the event of a release.
- A base of constraints: it contains all the mechanical laws and the interaction message(s). The base of constraints contains the set of the constraints having a relationship with the field concerned. For example, a constraint can read like "Wall Thickness > 1 mm" to point out the limit of manufacturing to avoid collapsing.

The KBS allows the user to describe the boundary conditions, loads, materials, etc. The CAD system and CAE system (mesh generator and analysis manager) are fully knowledge driven. They are usable by either CAD experts or mechanical engineers, and ensure a good usage and quality results.

The difficulty of the AM and topological optimization coupling is based on two problems:

- Topological optimization requires FEM resolution and a fine material characterization (new optimization algorithms can integrate non-linear material behaviors)
- Constraints defined in topological optimization need to be linked to the AM process to correctly parameterize the solver. For example if the AM process knowledge is not defined in the topological optimization solver, you will get too thin walls which cannot be manufactured (see a test-case on Figure 3).

3.2. *Material and manufacturable process characterization*

Rapid prototyping uses a "main material" and a "support material". The support material is either left into the prototyped model or cleaned out, which implies an economic damage for the manufacturer. In most cases the support has no structural role and becomes a manufacturing residue. The structural approach remains fixed and does not take different stresses into account.

Saving material can be important for the prototypist. This saving can be obtained either on a shape part but also on a functional part.

Additive manufacturing processes (Figure 2) require the selective application of thermo-physical and/or chemical mechanisms to generate a part. Thus, it is possible to produce parts with different characteristics, depending on the method used and the process parameters. However, complete testing of all part characteristics is neither cost-effective nor technologically feasible. Therefore, when formulating part specifications, the nature and scope of testing is an important issue.

To deal with the use constraints, we started a series of tests to characterize the material mechanically and

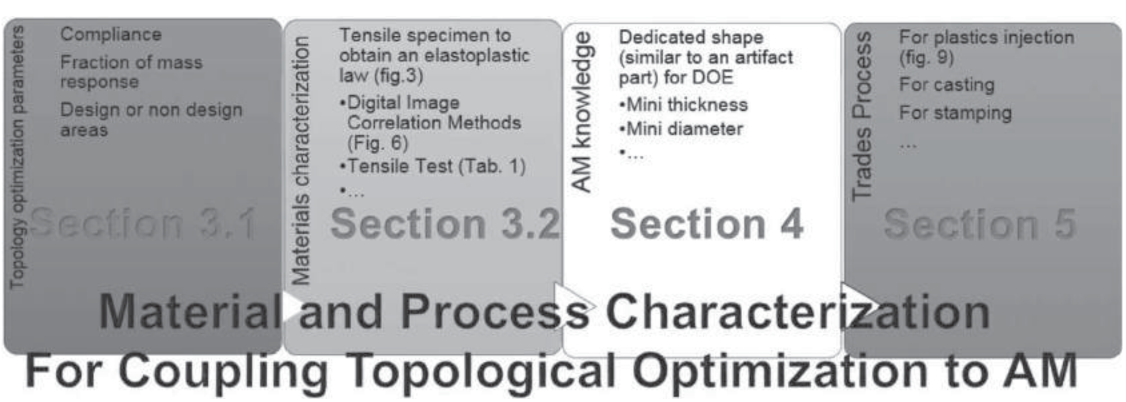


Figure 2. Process of our methodology.

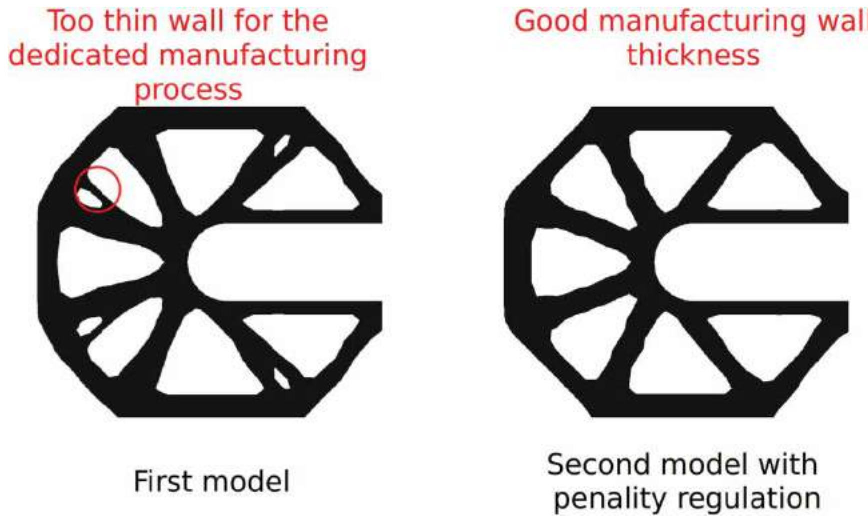


Figure 3. Test-case on C-CLIP for l the management of too thin walls.

dimensionally. This stage will enable us to identify the mechanical limits of the material provided by the manufacturer without any data.

The experimental approach is based on the using of standardized specimens manufactured by AM. The specific measurement tools are used to get behaviors data like the tensile strength. We carried out some tensile tests paired with a two-dimensional system of strain gauges (Camera distortion 3D Aramis GOM mbH[1]), on the basis of the implementation of F. Abbassi [2] work. Like F.Abbassi [2], we used the Aramis device to obtain the image correlation. This device allows the measurement of the displacement fields on a planar surface: a single camera acquires a sequence of images of a planar object under plane strain or stress during the deformation process. The displacement of many points distributed on the surface of the object are calculated from the grey level analysis of the images. A digital image correlation (DIC) in 2D method was used to measure the displacement fields at the surface of the specimens during the tensile tests. Tensile tests were used to determine the constitutive material behavior for implementing data in topology optimization and were carried out to determine the material parameters which impact the development data.

For different materials (Metals, Plastics, Composites, Concrete, Biomaterials, etc.) and under various environmental conditions (Room temperature, Elevated humidity and temperature e.g. inside climate chambers, or High elevated temperatures e.g. ovens, inductive heating.

For the characterization test, we developed a series of specimens of standard traction type CAMPUS ISO 527-1 /-2. The specimens were printed on the EDEN 260V printer™ matter VeroBlack™. The tensile specimens were arranged in several directions to quantify the influence of the manufacturing orientation on the mechanical characteristics (see Figure 4).

We were able to determine the Stress-strain curves, the stress and strain ratio, Young's modulus (E-modulus) Description of stress and strain-operation in the area of elastic deformation and finally Rp02, which describes the change-over from elastic to plastic deformation and is typically determined by shifting the line to gradient strain value of 0.2%. On Poisson's ratio, we were able to put a tactile clip extensometer on the specimens but we were restricted to a local measure.

Therefore, we chose to use the Digital Image Correlation (DIC) Method for Characterization Tests (see Figure 5) to quantify the measurement results Full-field 3D surface, 3D displacement and strain. We didn't know the material behaviors between these anisotropic or isotropic features, so we selected cross correlation image to find them out. This technology presents numerous advantages. First, it is a non-contact measurement which is independent from material and temperature. In addition, it is a solution delivering complete 3D surface, strain and displacement results where a large number of traditional measuring devices are required (strain gauges, extensometers ...) and give a local result.

During the tensile tests, an analog value of the load is automatically recorded to synchronize the tensile machine and DIC measurement results and to calculate the material parameters (see Figure 6).

The tensile tests resulted in usable data that we summarized in Table 1.

To calculate Poisson's ratio, we privileged an optical technique for its non-intrusive characteristic, its high spatial resolution and sensitivity. Test specimens were arranged in several directions to quantify the mechanical

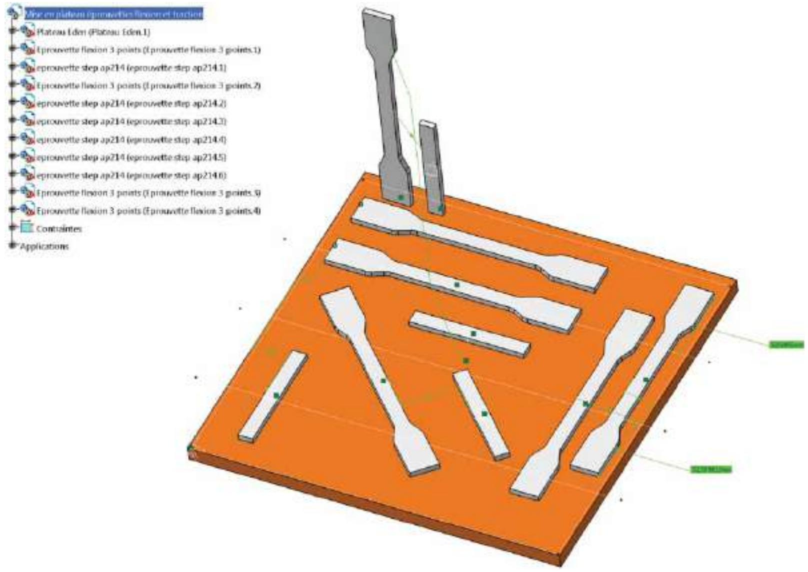


Figure 4. Tensile specimens orientation.

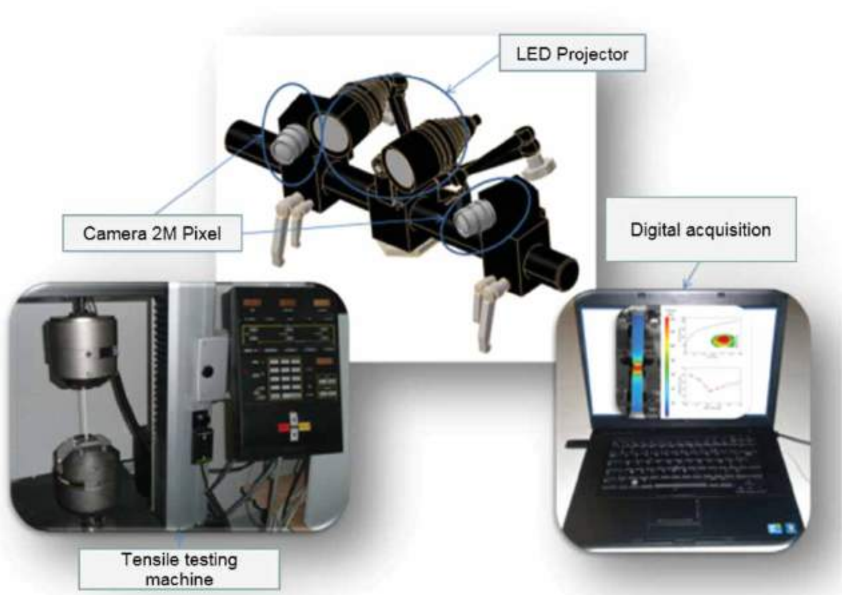


Figure 5. DIC measurement Device.

Table 1. Tensile strength summary.

Tensile strength tests	Test 1	Test 2	Test 3	Test 4
Rm (Mpa)	67	64,25	64,5	67,25
Re (Mpa)	46,4	47,17	46,5	43,72
Young Modulus E (Mpa)	2000	2069	1990	2118

Table 2. Summary table of average Poisson's ratio for specimen VeroBlack™

	ET1	ET2	ET4	ET5	ET6	Average
L0	94.903	88.4	19.507	91.122	87.109	
l0	9.1	10.401	9.1	9.088	11.701	
L	97.227	92.733	20.122	97.079	91.369	
l	9.002	10.171	8.98	8.846	11.472	
ν	0.439	0.451	0.418	0.407	0.401	0.423

manufacturing influence. The results of the operation of the measurement by 3D correlation (Figure 6) to obtain Poisson's ratio are summarized in Table 2.

Tensile tests provided usable data, allowing us to establish a Young's modulus of 2045MPa. These tests established a reference value for our calculations, specific to our protocol and much more accurate than the outcomes provided by the manufacturer from 2000 to 3000 MPa. Design of Experiment [7] [15] [22].

For Poisson's ratio, we favored an optical technique for its non-intrusive measure, high spatial as well as its

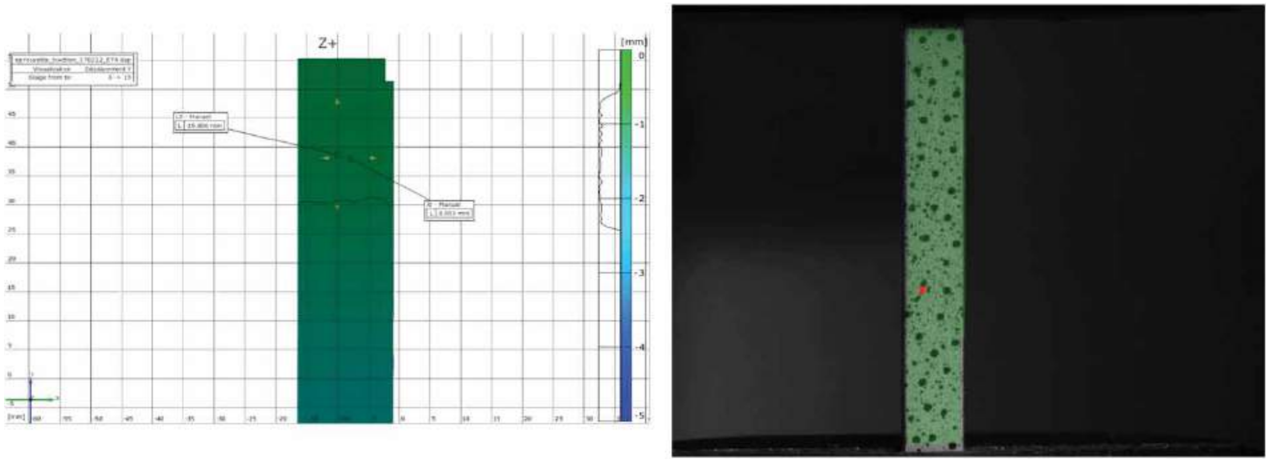


Figure 6. DIC measurement example.

high sensitivity resolution. The specimens were arranged in several directions in order to quantify the influence of the manufacturing direction on the mechanical properties. The results of the measurement operations of by stereo 3D image correlation (Figure 7) to get Poisson's ratio based on the "unitary transverse contraction of unit axial elongation ratio" helped establish a Poisson's ratio of 0.423 for the rest of our simulations.

4. Integration

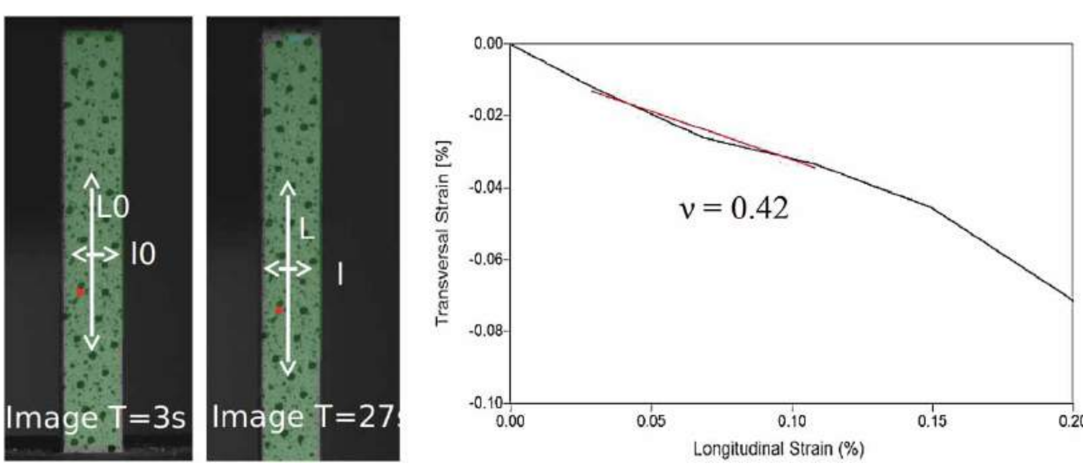
The experimental process to recover AM knowledge is based on two types of specimens

- ISO campus norm specimens manufactured by AM process: the aim is to determine the material behavior (typically the elastoplastic law) for further simulation as explained in the previous paragraph
- Specific shape specimens also manufactured by AM process: the aim is to capitalize knowledge to determine parameters like thickness/height limit, pocket depth allowed for powder evacuation, etc.

We can see on Figure 8 different manufacturing directions and shapes of the test parts. Those configurations allow the determination of risk factors.

Our approach involves the study of three very important factors for the topological optimization:

- The minimum thickness printable and cleanable without any part deterioration. We seek to maximize the minimum thickness of the wire cloth (final material) without losing any geometric or morphological quality of the part
- The minimum diameter printable and cleanable without requiring any mechanical cleaning: the objective is to define the best channel dimensions for the cleaning of the internal structure of the piece (allowing the powder evacuation)



Setting up of bi-limits sides on the two captured images in the elastic box

Poisson's ratio determination

Figure 7. Results of the measurement operation.

Table 3. Results of DOE analysis.

Parameter	Operator	Value	Result
Thickness	<	1 mm	Non feasible (matter collapsing)
Thickness	=	2 mm	Deformation for height > 10 mm
Thickness	=	3 mm	Deformation for height > 40 mm
Width	>	15 mm	Cleaning constraint

To help the global strength, pins can be added

— The maximum height which corresponds to the ratio between the projected length and height of the part which could cause a collapse.

We developed DOE (Design of Experiment) for different tests: laser temperature impact, thickness and height allowed (with cleaning process), manufacturing orientation, plate placement etc.

Table 3 shows the results used in optimization parameters.

The material characterization and factors, which impact the topological simulation, were introduced in the numerical simulation. An AM dedicated scenario was developed. For instance, it is limited to one objective: the weight gain.

The first step of this scenario was to define design variables like the penalization factor as we explained before. This penalization factor was defined according to the minimal thickness obtained by testing. We then defined two specific responses:

— The compliance response. The compliance is the strain energy of the structure and can be considered a reciprocal measure for the stiffness of the structure. A global measure of the displacements is the compliance of the structure under the prescribed boundary conditions (see equation 4 with K the stiffness matrix and U the displacements)

— The fraction of mass response. The fraction mass response is the material fraction of the designable material mass. It corresponds to a global response with values between 0 and 1. This allows the user to specify intuitive factors like "I want to gain 30% of mass", value transcribe as 0.3 in our program.

The next step was to minimize the compliance. Generally, in optimization, the compliance is used to evaluate the stiffness. Minimizing the compliance means having a stiffer structure. The higher the compliance, the more important the stiffness. (See scenario on Figure 9).

5. Application

The optimized model in direct .stl format is the implementation of rules in a multi-criteria optimization tool.

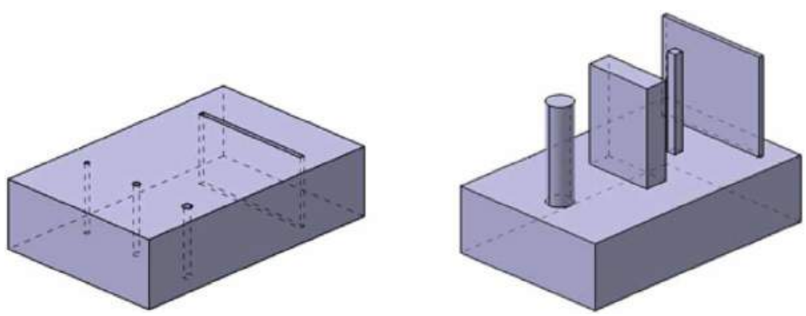


Figure 8. View of the different methods of manufacturing.

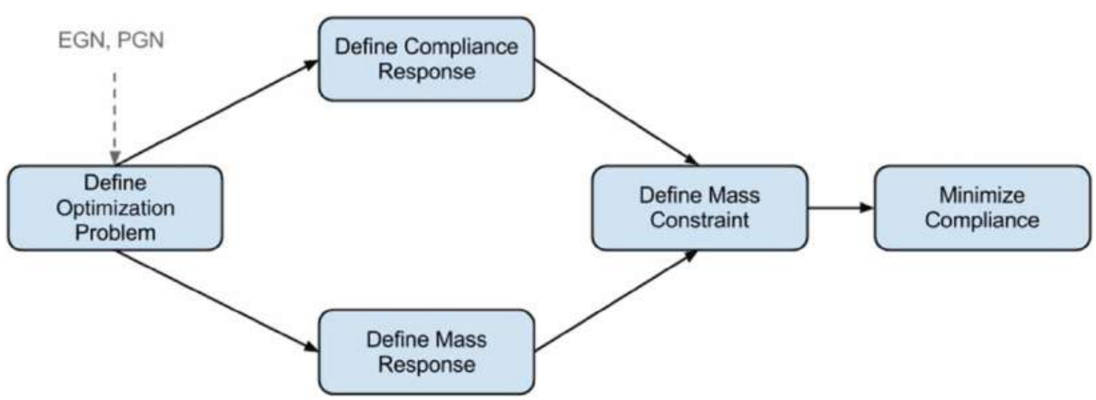


Figure 9. Mass scenario for topological optimization in AM.

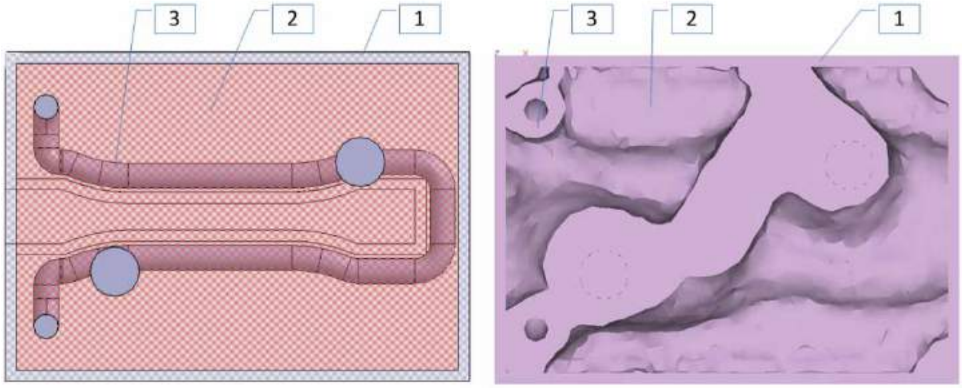


Figure 10. Optimized cooling system view.

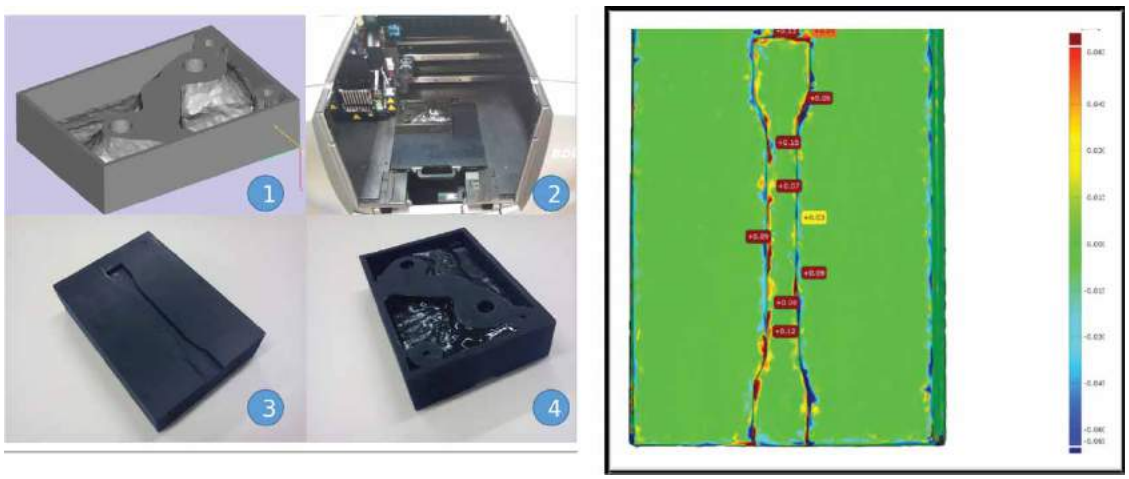


Figure 11. Optimized cooling system view.

These rules are divided into four categories:

- "Materials" (Poisson's ratio and Young's modulus)
- "Knowledge Management for additive manufacturing"
- "processes trades related to the use of mold inserts for the plastics industry". (Injection pressure, injection and mold temperatures, cycle time)
- Topology optimization (definition of design and non-design areas, see Figure 10 . . .)

The additive manufacturing technology enables all the possibilities of topological optimization while including the plastics business constraints. Besides, an optimized cooling system with its file is feasible (Figure 9), in this case the Polyjet ©technology was used. Pictures 3 and 4 of Figure 11 show the insert made using VeroBlack [14].

We intended to prove that an insert optimized with our methodology would resist as much as an unoptimized insert. So we placed two inserts in a symmetrical mold. By integrating the parameters determined during the phase of rheological simulation (injection pressure, injection and mold temperature, and cycle time), we injected 50 specimens prior to the degradation of the mold. In order to follow the evolution of the wear, we scanned inserts with a 3D acquisition system. The operation was performed every 10 injections. The 3D scanner offers an accuracy of 40µm (comparative study of 6 different systems [5]). Figure 11 corresponds to the last scan which was estimated as 'acceptable' (criterion set at 0.1 mm of wear).

6. Conclusion

This article presents a numerical optimizing method for improving the internal structure of models produced by additive manufacturing. The method integrates technical data to reach a balance between use and mechanical behaviors through round robin tests (DOE). A Knowledge Based System (KBS) was developed to manage the AM process and material characterization for the topological optimization integration. First of all, the aims were to reduce weight and save material (ROI) while keeping the mechanical properties of the model. Secondly, we established several tests throughout our approach thanks to a study case (injection mold) in order of to check the outcomes.

This optimization approach is relevant for other processes. It requires the crosscheck of technical data, but a centralized knowledge base should simplify the process in the coming years.

Note

1. www.gom.com

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