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Abstract:

In the rapid prototyping area, technologies used a construction material and a support material to manufacture geometry. The support material is sometimes conserved in the prototyped part and cleared on its outside. This elimination of support material involves a cost for the user. In some cases, the support hasn't structural rules and becomes a manufacturing residual which goes against the aims of ecodesign. This article presents a topological optimization application on a part produced by rapid prototyping. The authors used the numerical simulation to optimize the part's structure and assess the mechanical strength for optimizing he internal topology of a part manufactured by rapid prototyping to save on the material. The results present design solutions which take in account the use context. More particularly, this paper handles the correlation between the virtual and mechanical results. Design For Manufacturing (DFM) approach is used through different mechanical tests necessary to set data of the numerical simulation. Furthermore, the manufacturing characteristics have been integrated to analyze the mechanical behaviors of structure. The study presents an alternative geometry through a design for manufacturing approach and topological optimization of a rapid prototyping application.

Key words: Rapid prototyping, DFM, mechanical characterization, topological optimization, MJM

1 Context and objectives

Since the appearance of rapid prototyping, different technologies emerged. The manufacturing by layers keeps a common characteristic and the additive manufacturing or 3D printing get developed to propose several materials. The complex geometries which need a manufacturing held are maintained by support material. This material can maintain of the external and internal surfaces of a part. In most cases, the support material is cleaned during the finishing or traped into the model. The cost of consumables is often expensive and the loss of material isn't considered. Environment impact is not negligible for materials made from resin.

Concerning the material model which is used to form the part, its topology structural has few evolved in recent years. The using context and the physical constraints aren't supported while the generating of the numerical structural. Numerical simulation purpose a lot of advantages in numerical optimization to present adaptive model with using constraints.

This article discusses two issues:

- The structural adaptation of part according to using constraints in the frame of the manufacturing by rapid prototyping.
- The weight reduction to save some material and the extraction difficulty during the finishing.

Our aims are defined according to a research approach applied to additive manufacturing and a specific machine.

We suggest to use the numerical optimization to present a topological model in implication several using criteria. The DFM (Design For Manufacturing) is used to integrate the manufacturing parameters to beginning of CAD and also the setting data of material obtained through the mechanical tests. We present the results through a specimen which is used to check more information. After an analysis step of results, we will show a case study on an injection mould.

This article shows the implementation approach of the integration process including mechanical stress analysis. The characterization of the materials of the process was conducted to implement effectively the topological optimization tool. The checking of the methodology relies on a case study: a mold insert. Each step of the process implemented (Implementation of knowledge capitalization, topology optimization) or cases are detailed in the article.

2 Technologies

We use different tools to produce the parts and optimize the intern structure:

- The Multi-Jet Modeling which has the same approach that inkjet but with a photosensitive resin. A post-treatment is often used to separate the support part [9].
- The stereo-3d image correlation based on the principle of photogrammetry. A calculation method of spatial intersection [1] allows us to realize a 3d reconstruction of the object. The displacement measurement points is achieved by tracking.
- The numerical optimization of forms. We distinguish three great categories of shape optimization in mechanical structures like: "the parametric optimization", "geometric optimization" and "topological optimization"[2].

This third category of optimization is an appropriate method for the design step of new part because it permits to develop concepts and to find solutions into the "no comfort" area. Using of numerical simulation in our study has been detailed in a previous article [7].

3 Implementation of the application

The rapid prototyping in additive manufacturing use the material couple "model material" and "support material". The support material is preserved into the prototyped part or cleaned which implies an economic loss for the manufacturer. Most of them, the support hasn't structural rules and leads to a manufacturing residue. The structural approach remains fixed and don't adapt to different stresses.

Gain material can be important both for the support material and / or material model. This gain can be obtained for a shape part but also for a functional part. The gain material is shown in the article [7]. The application starts with the characterization of material from the distributor.

3.1 DFM Approach

DFM approach [10] and [8] is used trough different mechanical tests in order to integrate as soon as possible of the necessary data to numerical analysis. Several manufacturing characteristics have been integrated to interpret the mechanical behavior of the structure, such as the layered manufacturing direction. The study presents a alternative geometry about existing structures through numerical simulation, mainly numerical optimization and Design For Manufacturing.

3.1.1 Materials characterization

To deal with the constraints of using of a part, we started a series of tests to characterize the material mechanically and dimensionally. This step will permit us to identify the mechanical limits of the material to provide design solutions and to set a using area.

The experimental approach is based on the using of standardized specimens manufactured by RP and measurement tools specific to obtaining behavioral data of the material submitted to a tensile strength. We realized a series of tests tensile coupled with a system of two-dimensional strain gauges (Camera distortion

3D Aramis GOM mbH[1]) on the basis of the implementation of the work of F. Abbassi [1] tensile test bench. Tensile tests are used to determine the constitutive material behavior necessary for implementing data in topology optimization.

Tensile tests resulted in usable data. We summarize them in the table below:

Tensile 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 1 : Tensile tests summarite

For Poisson's ratio, we privileged an optical technique for non-intrusive character, its high spatial resolution and sensitivity. Test specimens were arranged in several directions to quantify the influence of the meaning of the mechanical manufacturing. Results from the operation of the measurement by correlation 3D (figure 1) for obtaining the Poisson's ratio are summarized in table 2.

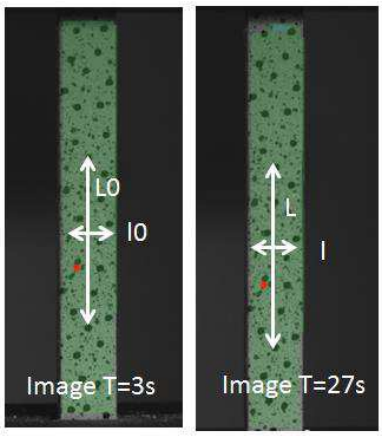

FIG. 1 - Setting up of bi-limites sides on two captures images in the elastic box

	ET1	ET2	ET4	ET5	ET6	Moyenne
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

Table 2: Summary Table of average Poisson‘s ratio for specimen Verowhite ™

[1] www.gom.com

3.1.2 Knowledge capitalization

In order to implement the geometric optimization tool, it is necessary to develop a knowledge base specific to the technology used in our study. Some works [5], present a qualification's process for a RP machine by the addition of layers through a test part to quantify defects and to determine the causes. However, these approaches do not tend to the technological limitations of the machine.
Our approach is to identify three important factors for geometric optimization of part :

- The minimum thickness printable and cleaned without damage to the room: we find to optimize the minimum thickness of the canvas (final material) without loss of geometric and morphological exhibit qualities;
- The minimum printable and cleanable diameter without mechanical cleaning: the objective is to size the best channels for the cleaning of the internal structure of the piece.
- The maximum height is the ratio between projected length and the height of the part which can cause a collapse.

Based on the work of B.H. Lee [3] for the determination of parameters influent on the quality of a functional prototype on FDM, a series of pieces allowed to determine the critical values depending on the context of use. A process has been implemented to integrate digital optimization parameters (the parameters are modeled as a formalism, called graphonumerical parameters GNP, developed during previous work [4]). This process (sub process of the general methodology) is a proposal to allow optimization of additive type RP pieces.

The optimization is to constrain the model as a percentage of volume material one wishes to win and to minimize the compliance (minimize compliance is to maximize the total stiffness based on a given effort; measure the compliance on a piece comes back to measure the work of external forces). Design variables correspond to extrusion direction, forms to repeat, to symmetries or limits on which the optimization algorithm is limited yet (wall thickness, maximum not to exceed, stress...).

3.2 Analyze

The first step of the methodology is to identify and define design spaces. A boolean operation in CAD software is needed to delimit the different zone. In our application, knowledge is linked with Catia V5 to help the designer in different important factor (like thickness of the skin which are linked with the specific RP process). The knowledge is dependant to two major factors:
- The calculus set: the part is maybe subject to specific set like loads, use impact (modal analysis for example). This item is not necessary, if the part to be manufactured is just for design view (touching function, assembly integration ...) the only set will to not fall down on his own mass.
- The RP process corresponds to previous detailed knowledge capitalization. It depends on the RP machine.
When the part is optimized, we add space shape for the support matter cleaning. This shape is pre-designed in CAD software and positioned in empty spaces (for instance in a manually way). We obtain in results a STL file which is put in the RP machine process software.
The optimized step is also defined as sub methodological process. The first step is to define design variables like the penalization factor (This penalization factor is defined according to the minimal thickness obtain by test). We define then two specific responses:

- Compliance response. The compliance is the strain energy of the structure and can be considered a reciprocal measure for the stiffness of the structure.

- 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 question like "I want to gain 30% of mass", value transcribe as 0.3 in our program.

The next step is to minimize the compliance. Generally, in optimization, the compliance is used to evaluate the stiffness. Minimize the compliance means to have a stiffer structure. Lower the compliance the higher the stiffness of the structure. So, the problem statement involves the objective functional of the strain energy which has to be minimized.

In order to validate the principle and the entire process, a parallelepiped has been tested. This form is subjected to a 400 Newton effort on the top and the base resting on a support. Several topologies were tested for win 30% of good material. Numerical optimization software used is Optistruct for the Altair Editor.

The different GNP are set according to the modelled knowledge. The desired percentage of gain material has been set here at 30% and the design, not to exceed maximum stress-related variable, was positioned on the yield strenght found through the physical tests (or 45 MPa). Figure 2 shows an optimized topology, built by 3D printing volume subject to a compression test and the results of the test for correlation with the numerical simulation.

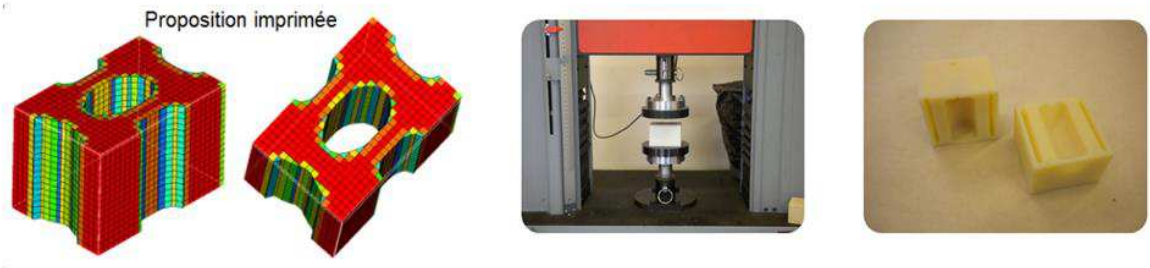

FIG. 2 - Optimization process

The analysis of the results allowed to show the curves between the full and the optimized model are similar (less than 10%) and the optimized part remains below the maximum stress in the optimization tool. The physical test showed for a 411N effort, a displacement of 0,018 mm and numerical simulation about 0.017 mm displacement (figure 3).

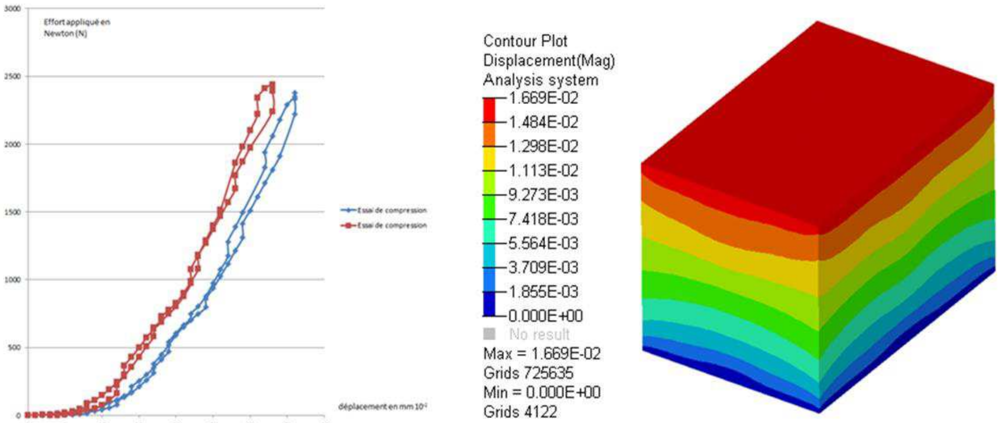

FIG. 3 –Mechanical tests and numerical simulation of the optimized part

4 Study in an injection mould

We present a case study to apply our search results to a specific model. We have chosen to optimize an insert for plastic injection mould. One of the issues that we are trying to raise concerns the production of small series good topic carried out by injection. In this context the achievement of a full metal mold is an economic important obstacle [7]. Our example is an insert by rapid prototyping taking into account induced efforts by injection and the thermal constraints of the mould.

Using our implemented tool with trade knowledge, we determined an optimized form with a target of 50% of gain material while retaining the ability of the insert to withstand pressures and temperatures of the process but also by integrating cooling channels predetermined on rheological simulation software. Figure 4 shows the digitally optimized shape its impression by MJM and rendered its final process after cleaning.

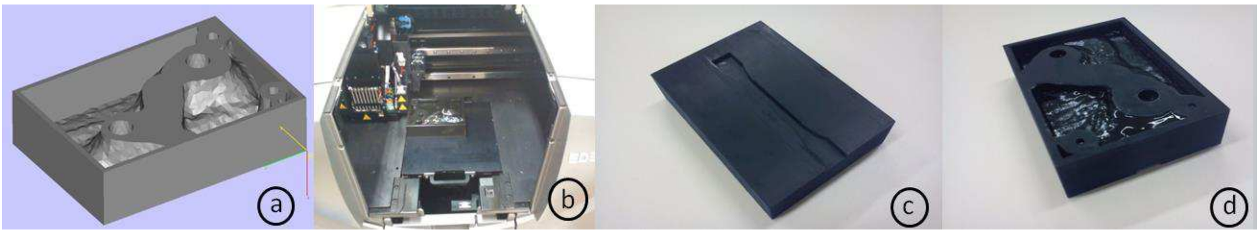

FIG. 4 - a) result numerical optimization - b) insert manufactured by process MJM - c) 3D print of the insert - d) topology optimization with taking into account cooling channels

The optimized solution has allowed to make a gain of quantify of model material of 60% and to lower the cost of returns from production of the insert close to 25%. This case study is detailed in an article published in European Forum on Additive Manufacturing 2013 [6].

5 Conclusion and perspectives

The main issue of this paper is the integration of simulation and optimization in the first phases of a manufacturing process to take into account the characteristics of additive manufacturing, in particular to save material.

The study was structured around several skills to implement this kind of design guided by numerical simulation and manufacturability by additive manufacturing. We have presented various models generated by numerical optimization. The optimization process has allowed to reduce the field of research applied to the internal topology of the piece to use constraints.

The results were successful to a methodology applied to industrial cases as the injection mould and also on another design object's (public type) which was not introduced in the article: a doorknob. The prospects are many if we apply the method to other applications and processes.

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