



Making the Most of Additive Manufacturing: Facing the Challenge

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Abstract

Additive manufacturing processes allow overcoming most of the design-related limitations. However, to make the most of this technology, it is necessary to design parts specifically for this process. From this standpoint, an aircraft part has been designed by using the topology optimisation method. Since “optimal” part is non-existent, two different “optimized” part designs have been realized, manufactured and compared to the initial part, regarding their mechanical performance. This study revealed different issues related to the selective laser melting process.

Introduction

It is often assumed that additive manufacturing (AM) will overcome the drawbacks in design and produce parts that will come directly from the imagination of their designers. However, the technological constraints of the different **AM processes** bring significant restrictions. Consequently, to make the most of this technology, it is necessary to design parts specifically for the additive manufacturing process. Three students of the Shape Memory Alloys and Intelligent Systems Laboratory (**LAMSI**) of the École de technologie supérieure (**ÉTS**), in

Montreal, have met this challenge by reviewing the design of a part usually produced by conventional methods. In this article, the students expose their approach to redesign a selected structural part with an objective to maximize its performances using AM.



Presentation of the Part and its Design Requirements

The experiment originated from a proposal for the **GrabCAD** design competition, sponsored by the **Fastening Systems & Rings d'Alcoa**[1]. The selected part for this study comes from an aircraft and has relatively simple shape: it can be found, for example, in the door hinges of the landing gear.

In this case, the design of the part envelope (represented by the gray portion in the figure below) is defined by the assembly requirements. The part is attached to a plate with four screws and is equipped with a spherical bearing at the tip.

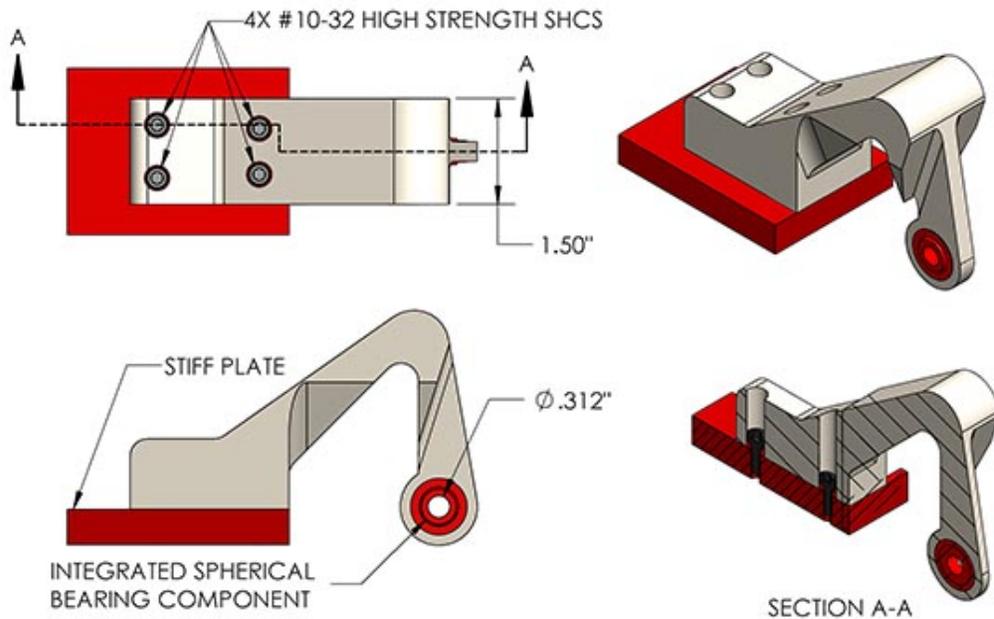


Figure 1 Original part to be optimized

As shown in the figure below, this part has three separate loading cases that were determined based on their service conditions. The specified material is 15-5PH stainless steel. The maximum stress value (Von Mises) induced in the part must not exceed 1000 MPa (the design safety factor is included in the loading cases).

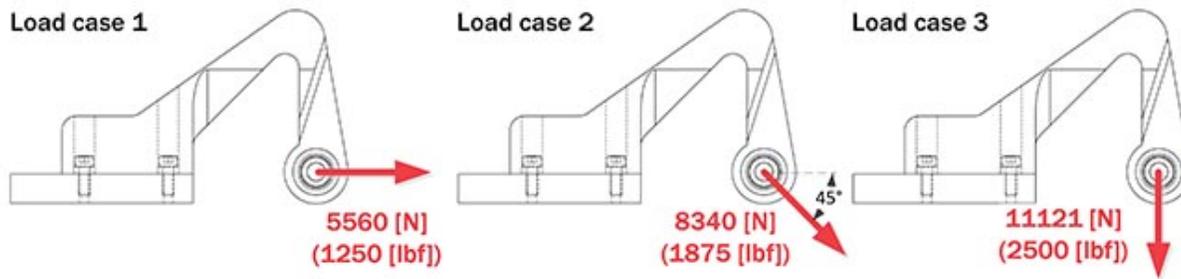


Figure 2 Three different loading cases to comply with

The competition also requires the use of the *selective laser melting (SLM)* process [4], subjecting the design of the part to the technological constraints that come with this process.

Design Optimization Process Using Topology Optimization

The optimization process of a structural part can be divided into five stages (as presented in the following diagram). Each of these steps requires the use of a separate engineering tool. Throughout the process, the designer must keep in mind the manufacturability of this part using the SLM technology. Contrary to popular belief for example, SLM manufacturing requires the use of supports for each overhanging (non-self-supporting) portions of the part[2]. In fact, the powder bed has a much lower density than the manufactured part. Therefore having no supports would cause the collapse of some portions of the part.

TYPICAL OPTIMIZATION SEQUENCE

Step 1 – Selection of a Part

which has a potential for optimization, and defines the optimization domain.



Step 2 – Topology Optimization

to find the optimal distribution of material according to the loads.



Step 3 – Modeling of the Optimization Result

Application of the computer aided design (CAD) software to obtain a 3D model for manufacturing.



Step 4 – Validation of the redesigned model

by using numerical simulations and the finite element method.



Step 5 – Final result

Subject to parametric optimization for further model refinement.

Result : The final part conforms to the stiffness and stress requirements while being lighter in weight.



Figure 3 Typical optimization sequence of a part

PRESENTING THE RESULTS:

Topology Optimization

To review the original design of the part, different topology optimization tests were performed using the INSPIRE software from solidThinking®.

Topology optimization uses the finite element modeling method to find the ideal material distribution in a given volume, in order to reach one or multitude of the design goals. Often, these goals are to maximize the stiffness (less displacement when loaded) or to minimize the mass of the parts, while preventing part failure during service [3].



In the present case, the optimization objective was the mass minimization. However, to diversify the optimization results, two shape constraints were applied: the constraint A (symmetry) and the constraint B (extrusion direction). The video below shows the topology optimization results with the mass minimization objective by applying the symmetry constraint to the part (constraint A), while respecting the strength criterion of the competition.

Modeling of the Optimization Results

The topology optimization results represents only the overall geometry of the final part. The designer has to remodel the part with a computer-aided design (CAD) software. Two parts which were obtained by using the CAD software Solidworks[®] (optimization A) and CATIA[®] (optimization B) are represented in figure 4. The marked difference which is observable between these two parts proofs that there exists a number of optimized parts, but never “THE OPTIMAL” part.

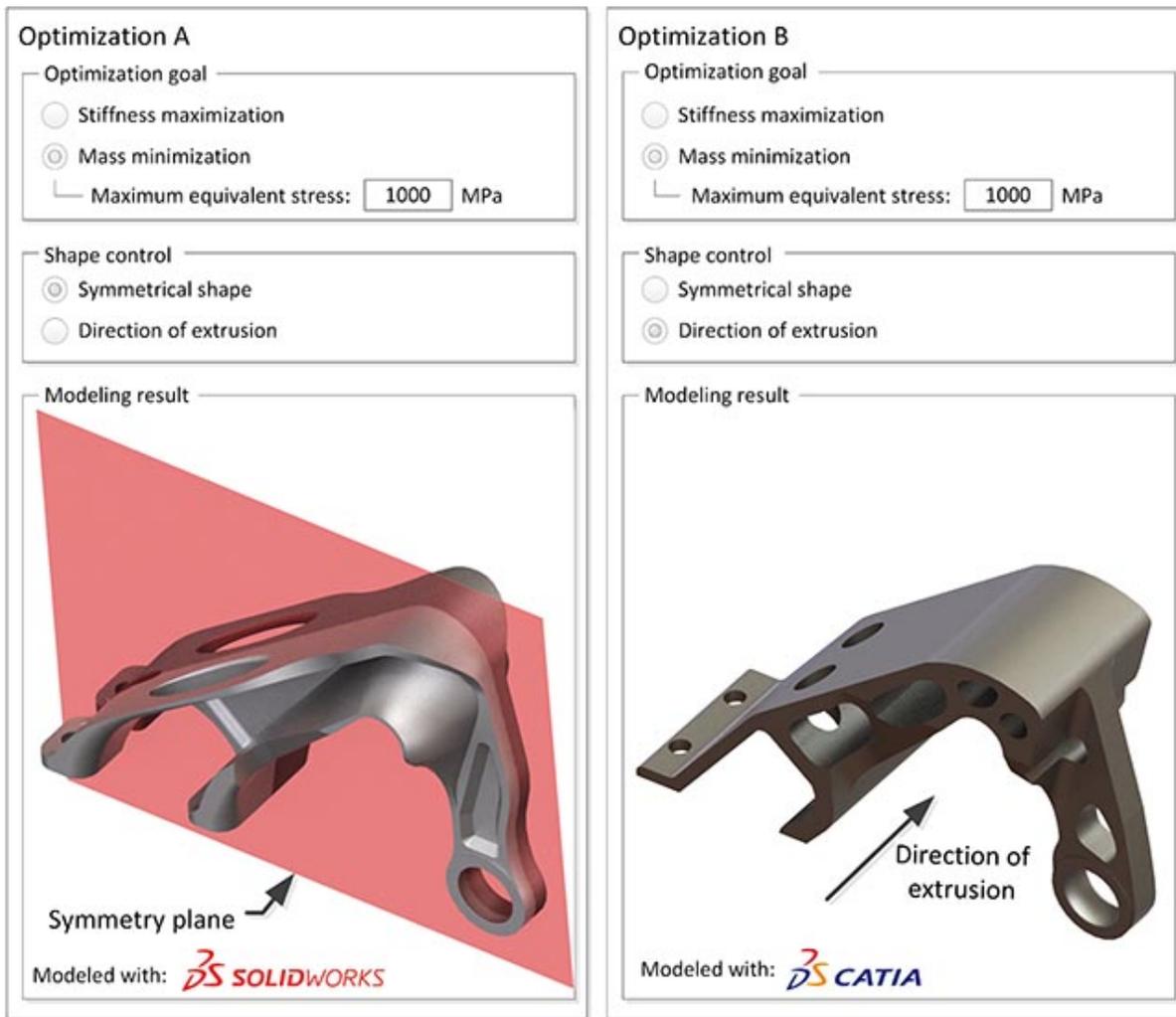


Figure 4 Settings for two optimization approaches and the modeling results

Validation of the Redesigned Model

After this, the new models were verified according to the design requirements using the finite element method (FEM) simulation software. In this case, the **ANSYS® Workbench** was used.



Here, different loads were applied in succession and the design criteria were validated. In most cases, the modeling and validation phases require a number of iterations. Ideally, this geometric refinement stage uses a parametric optimization feature that interconnects the CAD and the FEM software.

Numerical simulations permit to compare the results of different optimization approaches. For this reason, the maximum equivalent stresses, the maximum total displacements of the spherical bearing axis for each of the three loading cases, as well as the masses of two different designs are represented in the table below and compared with the initial design.

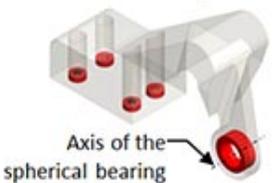
Concepts	Initial envelope	Optimization A	Optimization B
Results			
Mass of the part [g] (Relative difference [%] vs initial envelope)			
	859	319 (-63)	357 (-58)
Maximum equivalent stress [MPa] (Relative difference [%] vs initial envelope)*			
Case 1 (5560 [N] @ 0°)	734	953 (+30)	936 (+27)
Case 2 (8340 [N] @ -45°)	769	997 (+30)	988 (+29)
Case 3 (11121 [N] @ -90°)	522	938 (+80)	794 (+52)
Maximum total displacement of the spherical bearing axis [mm] (Relative difference [%] vs initial envelope)			
Case 1 (5560 [N] @ 0°)	0.9	1.5 (+68)	1.6 (+75)
Case 2 (8340 [N] @ -45°)	0.7	1.2 (+66)	1.4 (+102)
Case 3 (11121 [N] @ -90°)	0.6	1.2 (+88)	0.9 (+48)
Scoring Q_σ (quality with respect to stresses)		→ Target : increase	
		1.67	1.76
Scoring Q_δ (quality with respect to displacements)		→ Target : increase	
		0.86	0.85

Table 1 Comparison of the optimization, modeling and simulation results. * Note that in all cases, parts A and B withstand the applied loads.

The last two rows of the table show the scores of the optimization quality with respect to stress (Q_σ) and displacement (Q_δ). These scores are expressed by the following equations:

$$Q_\sigma = \sum_{i=1}^3 \omega_i \frac{|\Delta m|_i}{\Delta \sigma_{\max_i}}; \quad Q_\delta = \sum_{i=1}^3 \omega_i \frac{|\Delta m|_i}{\Delta \delta_{\max_i}}; \quad \sum_{i=1}^3 \omega_i = 1$$

where i is the load case, $|\Delta m|_i$ is the relative mass reduction (%), $\Delta \sigma_{\max_i}$ and $\Delta \delta_{\max_i}$ are, respectively, relative increase (%) in the maximum equivalent stress and the maximum displacement with respect to the reference case (original part). Finally, ω_i is the weighting importance factor of every load case and its values were chosen as to give the same importance to every case.

It should be noted that *Optimization B* gives the best quality optimization scoring in terms of resistance (stress), while *Optimization A* offers the best scoring in terms of stiffness (displacement). Nevertheless, both optimization cases, A and B, meet the design requirements.

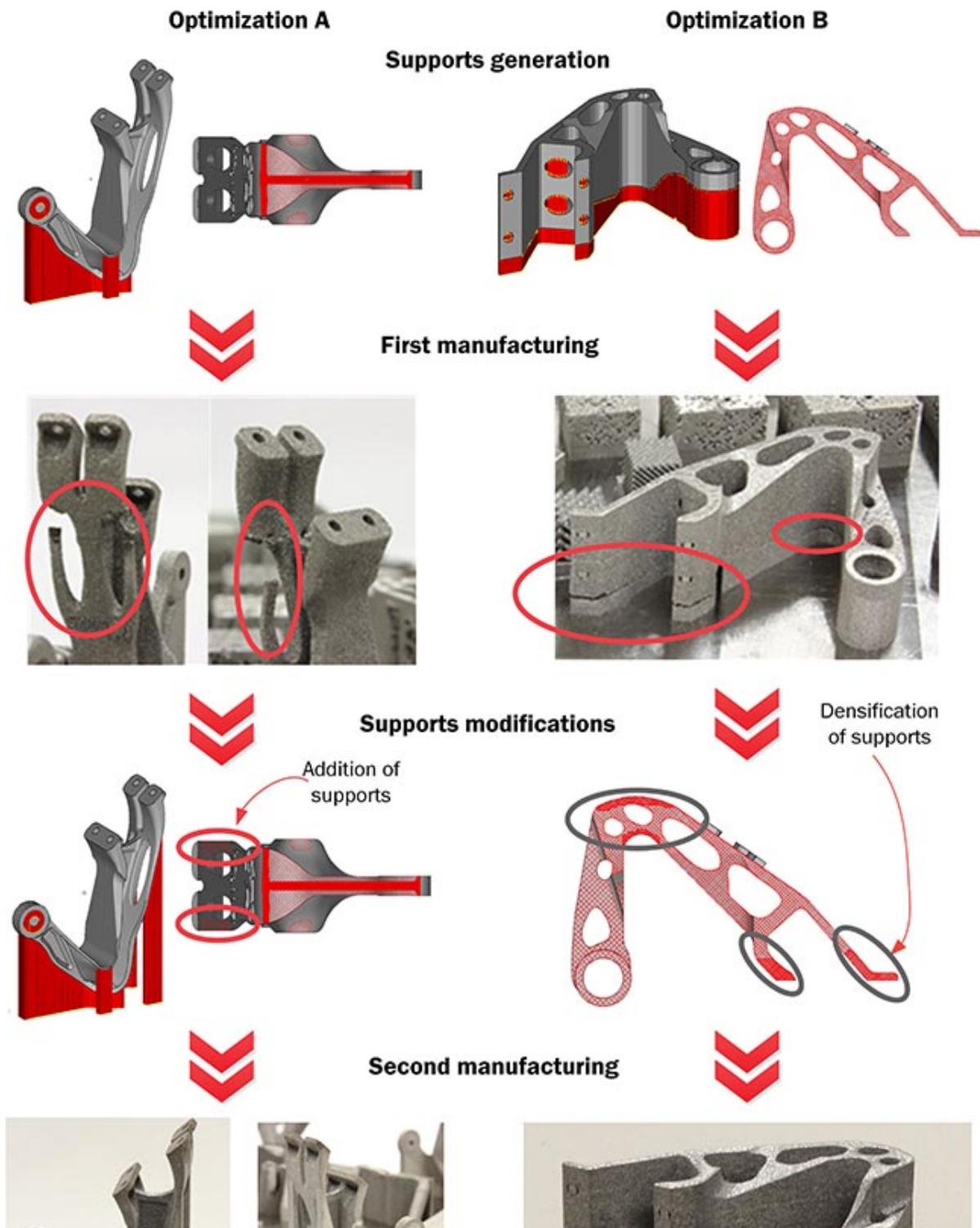
Preparation for Manufacturing

The preparatory work for manufacturing consists of the addition of supports (areas marked in red in the figure below) and selection of the part orientation in the AM system. This choice greatly impacts the manufacturing time



as well as post-manufacturing operations when removing the supports. This preparation was done using the **Magics** software, developed by Materialise.

Despite extensive knowledge of the SLM-related technological constraints, the first manufacturing attempt was unsatisfactory as is shown in the following figures. These manufacturing defects can be explained by insufficient supports and their inappropriate configuration. Nevertheless, the addition of new supports led to successful production in the second attempt.





Final parts



Figure 5 Manufacturing steps of the parts

Points to Remember:

- Additive manufacturing shows a strong potential for part optimization;
- Topology optimization is a mathematical algorithm that allows designers to find the best material distribution based on the specific design requirements;
- There is a difference between the optimized part and an optimal part;
- AM requires special knowledge to be successful [5];
- Design for AM is not yet a well-mastered science and frequently requires several trial-and-error attempts to produce a successful part. To facilitate this process, numerical tools capable of simulating SML process are in the course of development at the LAMSI.

Auteurs



Bruno Jetté (team member) is a masters' student in **mechanical engineering** at the École de technologie supérieure (ÉTS), in Montréal and a member of the **LAMSI**. His projects focus on structural optimization of parts for additive manufacturing by incorporating regular lattice structures.



Morgan Letenneur (team member) is a masters' student in **mechanical engineering** at the École de technologie supérieure (ÉTS), in Montréal and a member of the **LAMSI**. His research focuses on developing new powders for additive manufacturing.



Mykhailo Samoilenko (team member) is a masters' student in **mechanical engineering** at the École de technologie supérieure (ÉTS), in Montréal and a member of the **LAMSI**. His projects include the study of fuel combustion phenomena in cell structures produced by additive manufacturing.



Professor **Vladimir Brailovski** is involved in several multidisciplinary projects requiring expertise in materials, design, and manufacturing processes. For the past 20 years, he has been deeply invested in the design and manufacture of devices in shape memory alloys and has achieved international recognition in this field. Additive manufacturing is a natural extension of his research activities in the field of shaping processes. He is a full professor at the mechanical engineering department of the École de technologie supérieure (ÉTS), in Montréal.

REFERENCES

[1] This competition was held from January 7 to February 7, 2016, and received around 320 design entries.

[2] To learn more about the manufacturing constraints of the SLM process, please refer to the Design Crucible document:

<http://www.crucible-design.co.uk/images/uploaded/guides/bs7000-part-2-a-management-guide-download-original.pdf>

[3] To learn more about topology optimisation, please refer to the book : « Topology Optimization : Theory, Methods, and Applications », (Bendsoe et Sigmund, 2003)

[4] For more information about the different additive manufacturing process, please refer to the following articles :

<http://substance.etsmtl.ca/fabrication-additive-un-tour-dhorizon-pour-aider-vous-y-retrouver-1-de-4/>

substance.etsmtl.ca/fabrication-additive-un-tour-dhorizon-pour-aider-vous-y-retrouver-2de4/

<http://substance.etsmtl.ca/fabrication-additive-un-tour-dhorizon-pour-aider-vous-y-retrouver-3-de-4/>

<http://substance.etsmtl.ca/fabrication-additive-un-tour-dhorizon-pour-aider-vous-y-retrouver-4-de-4-2/>

[5] To discover the additive manufacturing in general, please refer to 3DHubs' document: <https://www.3dhubs.com/knowledge-base#section=featured>.

IMAGE REFERENCES

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