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Topology optimization and additive manufacturing: Comparison of conception methods using industrial codes

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Abstract

Additive manufacturing methods provide an increasingly popular industrial means of producing complex mechanical parts when classical methods are not suitable. The main advantage of these methods is the great freedom they give designers. At the same time, theoretical and numerical topology optimization tools can be used to simulate structures with complex shapes which exactly meet the mechanical constraints while requiring as little material as possible. Combining topology optimization and additive production procedures therefore seems to be a promising approach for obtaining optimized mechanical parts. Nonetheless structures obtained via topology optimization are composed of parts of composite densities which can not produced via additive manufacturing. Only numerical structures made of full or empty spaces only can be produced by additive methods. This can be obtained at the end of computational optimization througth a penalization step which gives the composite densities from 0 to 1 the values 0 or 1. This means that the final part is different from the best solution predicted by topology optimization calculations. It therefore seemed to be worth checking the validity of an engineering approach in which additive methods are used to manufacture structures based on the use of industrial topology optimization codes. Here the authors propose to study, in the case of a simple mechanical problem, that of a metal cube subjected to a given pressure, three procedures, which differed in terms of the code and type of topology optimization calculations performed and the level of penalization applied. The three structures thus obtained were then produced using additive methods. Since all three structures proved to be mechanically resistant, the three procedures used can be said to be valid. However, one of them yielded better compromise between the mechanical strength and the amount of material saved.

Keywords:

Topology optimization, Computer aided engineering (CAE), Additive manufacturing, Selective Laser Melting.

1. Introduction

One of the traditional manufacturing methods most widely used in the mechnical industries consists of removing excess of material from a block until only the desired shape remains. However, although computer aided manufacturing tools and machine tools are being constantly improved, it is sometimes very difficult or even impossible to produce parts with complex shapes such as intertwined, imbricated, assembled and alveolar parts only by subtractive manufacturing. *Additive Layer Manufacturing* (ALM) methods, which are commonly known as "3-D printing" methods, are a set of mechanical procedures which can be used to overcome the technical limitations of classical approaches while giving greater freedom of design. These methods can be applied using metallic or plastic materials in the form of powder or threads, which are melted and soldered layer by layer, depending on the Computer Aided Design (CAD) trajectory of a laser or electron beam, an electric arc or a thermal resistance. After being developed in the 1960 as a means of producing prototypes and scale models, additive manufacturing processes were gradually improved in order to meet the demand for more functional mechanical parts and tools [1]. These processes can be used either to improve and lighten previously existing parts, or as a means of quickly manufacturing new products with complex shapes at a similar cost to that of conventional procedures [2]. In view of these advantages, many studies are now being performed to further improve these methods and give greater design freedom and precision and a wider range of materials while reducing the production time to a minimum. The best-known ALM methods include FDM (*Fused Deposition Modeling*) [3], DMD (*Direct Metal Deposition*) [4] and SLS (*Selective Laser Sinterning*) [5] methods, which are faster than classical methods but do not always meet the requirements of mechnical strength, fatigue resistance, porosity and surface rugosity.

Selective Laser melting (SLM) methods, in which a laser is used to selectively fuse a layer of powder according to a specific pattern, seem to provide an attractive means of overcoming the problems inherent to classical methods because the fast cooling speeds make it possible to produce complex parts with very fine microstructures. These methods can be applied to various materials such as polymers, ceramics and metallic materials. During the production of a metallic component, the laser melts not only the powder bed, but also part of the underlying layer, so that metallurgical bonds are formed between the laser weld seams and the previous layers. These method give similiar mechanical properties as those obtained using conventional procedures. However, since the machine parameters adopted during the production process directly affect the mechanical properties of the components obtained, these parameters have to be finely adjusted in order to obtain high-quality mechanical parts. SLM manufacturing is conducted in controlling first the laser parameters: the power, the scanning velocity and the beam diameter. Then system parameters have to be defined. They correspond to the density and depth of the powder bed , the seam width , the hatch distance between two adjacent seams, the scanninging trajectory and the hatch angle [6,7,8]. The environmental parameters which have to be regulated include the protective gas and the pre-heating temperature.

If several studies [9,10,11,12,13] have shown that the final quality of SLM parts depends strongly on the laser parameters, it is possible to obtain a relative density of almost 100% by optimising the laser parameters [14]. In the same way, the residual loads and the distortion can be highly reduced by adjusting some of the the environmental parameters [15,16,17]. The SLM method, after calibration, can be so seen as a real means to produce parts of high mechanical quality comparable to or even better than those obtained using traditional methods.

Once all the parameters have been calibrated, the cost of additive manufacturing processes will depend directly on the mass of the material to be fused. The cost therefore depends on the volume of the final part rather than on its complexity, contrary to what occurs in the case of subtractive manufacturing. To ensure greater cost efficiency and better performances, it is therefore necessary to lighten the part by

decreasing the amount of material to be deposited and encourage designers to increase the complexity. One way of achieving this is to combine ALM processes with intelligent design based on topology optimization methods.

Topology optimization methods [18] provide an ideal numerical tool for automatically determining optimum shapes without having to take the manufacturing process into account, based on specifying one or two mechanical criteria to be minimised and a given design space. The optimization potential of these methods is much greater than that of classical optimization methods of size [19,20] or shape [21,22,23,24,25,26]. Indeed topolgical optimization allows changes to be made not only in the geometry of the structure, but especially in its topology, modifying the number and connectivity of components and creating in the medium some boundaries, branches and holes. With topology optimization methods, the aim is not so much to look for the most suitable shape, but rather for the optimal distribution of material and void regions inside a predefined design domain for a given set of loads and boundary conditions. In the continuous case, the design variables are the number, connectivity, shape and location of voids (Fig. 1a) whereas they are the thicknesses or cross-sectional areas of structural members (Fig. 1b) in the discrete approach.

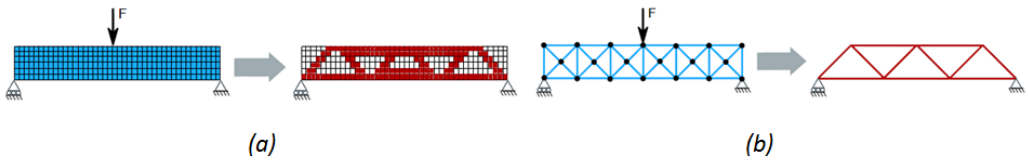

Fig. 1. Principles of topology optimization in the (a) continuous and (b) discrete case.

In most industrial cases, this approach yields satisfactory solutions, which are fairly complex and not always very intuitive. Contrary to conventional manufacturing, ALM methods give near-complete freedom of design and makes it possible to benefit from the powerful numerical solutions which can be "printed out" directly without any restrictions. The significant decrease in the volume of material used immediately shortens the production time and makes for considerable savings.

During the last few years, modules of topology optimization have been integrated into the industrial calculation codes. The main software programs providing topology optimization modules include Optistruct, which comes with *Hyperworks* (Altair), *Tosca* (FE-Design), which comes with the Abaqus code (DS Simulia), MSC-Nastran (MSC Software), Genesis (VR&D), which comes with Ansys Mechanical, Protop (CAESS), which comes with *Creo* (PTC), PLM Software, which comes with *NX/CAE* (Siemens), and Inspire (SolidThinking). All these codes may differ in terms of the behavioral laws involved and the algorithms used. In the field of industry and in the services of research and development, Abaqus and Optistruct codes are today the most used.

If SLM methods can clearly take advantage of topology optimization codes, the optimized solution may greatly depend on how the problem is defined and what are the objectives and constraints. In addition, the step which concerns the traduction of a theoritical solution into a manufacturable part is not so evident. Indeed, the best optimization solution is often composed of composites densities ranging from 0 to 1. To be produced by SLM method, this solution needs first to be transformed and possess local densities of 0 or 1 only. This is done at the end of computational optimization througth a penalization step. This step can be done automatically or manually. This tranformation can result in a final structure that is be different from the one initially predicted by the topology optimization computation. It therefore seems to be worth checking the validity of an engineering approach based on the use of industrial topology optimization codes to manufacture structures via SLM method. The aim of the present study is to show in a pragmatical way the real potentiel of combining additive manufacturing procedures with an industrial commercial software for topology optimization. Optistruct (Altair) and Tosca Structure in Abaqus (DS Simulia) which are used the most were here considered. The authors opted for a simple

case of topology optimization, that of a cubic volume of Inconel 718 withstanding a given compression load. Using the Abaqus and Optistruct codes, three numerical topology optimization methods were chosen to calculate the lightest possible structure. These structures were produced using SLM methods and subjected to mechanical tests in order to assess the performances of the three conception methods used for this purpose.

2. Material & Methods

The aim of the authors was to analyze the real advantages of combining SLM fabrication with topological optimization and to compare using two commercial codes the performances of different formulations of problems on workpiece resistance and matter savings. To do this, they considered the simplest topological optimization problem, that of a cubic volume capable of resisting a given compression load. After optimization simulations, the different solutions were manufactured via SLM, observed under a microscope and experimentally tested to characterize the actual mechanical behavior. The structure that has withstood the required load with the least matter has indicated the best way to formulate a topological optimization problem for SLM manufacturing. The various steps of the methods are described below.

2.1. Description of the test case of topology optimization

The authors chose, as case study, a cubic structure of 20 mm of edge made of Inconel 718 and subjected to 30 Mpa of uniaxial compression. They used industrial codes to optimize the topology of the structure by seeking to minimize the volume of material just needed to ensure the mechanical strength of the structure with a safety factor of 1.9. The cube shown in Fig. 2 was divided into two sections, one of which is called the design space, corresponding to the optimizable volume, and the other corresponding to upper and lower 1mm-thickness layers which was not involved in the optimization procedure. The lower layer was encastred and the upper one was subjected to a pressure of 30 MPa. The cube was meshed into 64 000 hexaedric elements and was given the material properties of Inconnel 718 produced by SLM (Table 1).

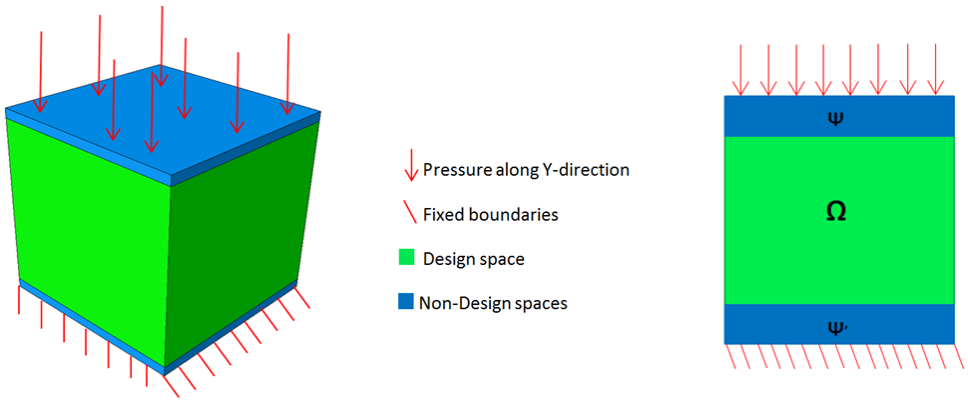

Fig. 2. A numerical model for the cubic compression chamber. In the topology optimization process, Ω is design space and Ψ and Ψ' the non-design spaces.

Table 1
Mechanical behavior of Inconel 718 produced by selective laser fusion and after thermal process. The Young modulus (E), the yield strength (Rp0.2) and the ultimate strength (Rm).

	E [GPa]	Rp0.2 [MPa]	Rm [MPa]
Inconel 718	**164**	**980**	**1232**

2.2. Problem formulations, design parametrization

2.2.1. The stress-constrained optimization problem (SCO)

Imposing stress constraints on topology optimization problems is an extremely important topic. The classical stress-constrained optimization problem consists of finding the minimum weight structure that satisfies the stress constraint and which is in elastic equilibrium with the external forces, that is, the design problem is in the form:

$$\min_{\substack{\rho \in [0,1] \\ K(\rho)\, u(\rho)=F \\ \sigma_{VM}(\rho) \leq \frac{\sigma_e}{f}}} V(\rho) \tag{1}$$

where

- K is the global stiffness matrix,
- σ_{VM} *and* σ_e the Von Mises and material yield stress, respectively,
- f a safety factor.

Here, ρ represents the material density of each element, directly used as the design variable, and varying continuously between 0 and 1; these represent the state of void and solid, respectively. Intermediate values of density represent fictitious material. In general, the optimal solution involves large gray areas of intermediate densities ($\rho \in]0,1[$) in the structural domain. Such solutions are not meaningful when the topology of a given material is looked for, and not meaningful when considering the use of different materials within the design space. Therefore, techniques need to be introduced to penalize intermediate densities and to force the final design to be represented by densities of 0 or 1 for each element.

One possibility which has proven very popular and extremely efficient is the "so-called" SIMP approach (*Solid Isotropic Material with Penalization)* also known as density method in the research community and introduced by Bendsoe in the late 1980's [27,28,29]. It consists of using a power law to relate the density to the mechanical properties of the material. SIMP method proposes the following equation:

$$\mathrm{K}(\rho) = \rho^p \cdot K^0, \;\; p > 1 \tag{2}$$

where

- K^0 denotes the stiffness matrix for the given isotropic material,
- p is a penalization exponent which usually ranges between 1 and 4.

With this approach, it is possible, by choosing p suitably, to penalize intermediate densities and promote a binary "solid/void" solution which can be more easily applied to manufacturing processes. Indeed, for a composite density of 0.5 for instance, increasing the exponent p will result in a smaller stiffness. This means for the optimization calculation that considering composite densities is uneconomical and that the corresponding material weight should be used differently promoting solid or void elements ; p equal to 3 is an optimal values so as to obtain almost binary solid/void solutions [30].

2.2.2. The continuous compliance optimization problem (CCO)

The SIMP method has been constantly developed and improved in books and articles [18,31]. Easy to implement, it can be used to process a wide range of objective functions and constraints (compliance, stresses, frequency, displacements and alternative physics such as eigenvalue problems). For the popular maximum stiffness optimization problem, the mean structural compliance is commonly used in most of the existing methods as the objective function to be minimized, and the constraint is imposed on a somewhat arbitrarily specified material volume V. Using the SIMP model, the minimum compliance problem takes the form:

$$\min_{\substack{\rho \in [0,1] \\ K(\rho)\, u(\rho)=F \\ K(\rho)=\rho^p K^0 \\ \int_\Omega \rho \le V}} F^T u(\rho) \tag{3}$$

where u and F are the displacement and load vectors, respectively.

2.2.3. The discrete compliance optimization problem (DCO)

An alternative form of the above problem is to consider the integer 0-1 (void/solid) compliance optimization problem [32]. Within the design reference space Ω, we seek to determine the optimal subset ω of material points represented by its characteristic function ρ which is written as follows:

$$\rho(x) = \begin{cases} 1 \text{ if } & x \in \omega \\ 0 \text{ if } & x \in \Omega \backslash \omega \end{cases} \tag{4}$$

The minimum 0-1compliance problem takes the form:

$$\min_{\substack{\rho \in \{0,1\} \\ K(\rho)\, u(\rho)=F \\ K=\rho \cdot K^0 \\ \int_\Omega \rho \le V}} F^T u(\rho) \tag{5}$$

2.3. Engineering approaches

Based on these above three specific formulations, the authors propose three different methods of resolution using Abaqus and Optistruct codes to optimize the topology of the cube test case withstanding compressive load.

The first method, called "SCO", consisted in solving the stress-constrained optimization problem in Abaqus. In this approach, the authors determined the minimum material weight while imposing that Von Mises stress did not exceed the elastic limit of Inconnel 718 divided by a safety factor of 1.9. At the end of optimization computation, manual penalizations were performed with different density thresholds of 0.25, 0.3, and 0.4 above which the density is set to 1 and below which it is set to 0, so as to obtain manufacturable structures.

In the second method, called "CCO", the continuous compliance optimization problem was solved in Optistruct. Here, several volumes to be conserved, ranging from 15 to 40% of the total volume of the cube, were imposed successively as optimization constraints. During the comptutation, the penalization exponant p is adjusted so as to produce 0-1 final optimized structure.

Finally, the "DCO" method consisted in solving the discrete compliance optimization problem in Abaqus for different values of volume constraint.

The penalization is one of the key points on which this study focuses. According to wether it is performed automatic or manual, penalization step results in manufacturable optimized solutions that whose mechanical behaviors may differ. To compare their mechanical behaviors, the final binary solid/void computational structures which were obtained via 3 models of topology optimization, were tested computationnaly applying the same compressive load as in the beginning and comparing the maximum Von Mises stress with the material yield stress.

2.4. Production of cube test-pieces via SLM manufacturing

The three optimized structures resulting from the numerical simulations were exported in STL format. The files were input to the SLM machine to produce the test-pieces. For each of the three optimization methods tested a sample of 3 test-pieces was produced. The material used was a powder consisting of spherical Inconel 718 particles ranging between 10 and 45 µm in size. The chemical composition of this powder is given in the following Table 2.

Table 2

Chemical composition of the Inconel 718 powders used (percentages).

Cr	Mo	Al	Ti	Fe	Nb	C	Ni
18.4	4.2	0.3	0.9	17.7	5.1	0.08	53.32

The nine Inconel 718 test-pieces were manufactered by our industrial partner Poly-Shape using SLM methods. The manufacturing parameters which were specifically optimized for use with this material were adopted. The final mechanical properties of Incoln 718 produced using these SLM parameters are reported in Table 1. These laser parameters a priori give parts with relative densities approaching 100%, which ensures that they will have similar mechanical characteristics (measurement accuracy, reliability, fatigue resistance, etc.) to those obtained using classical methods such as molding or machining. A Concept Laser M1 machine was used at a power of 200 W. The scannng velocity was set at 400 m/s and the beam diameter at 80 µm. During the production process, the chamber was heated to a temperature of 80°C using Argon as the protective gas. These environmental parameters were chosen in order to reduce the distorsions and residual stresses in the resulting parts to a minimum. The material was deposited layer by layer in the same direction as that in which the cube is loaded. In the present case, each of the layers was 40 µm thick (each sample consisted of 500 layers). Temporary supports designed by Magics were used to hold the test-pieces in place during the production process.

To analyze the influence of SLM manufacturing on the microstructure of the samples, the porosity was measured at the surface with a light microscope and using the ImageJ software. From photos of the surface, porosity was measured in identifying empty zones based on differences in the contrast, and calculating their percentages in comparison with the total area covered by the image. The relative density obtained was used to validate or not the choice of process parameters used to produce the samples.

2.5. Experimental mechanical tests

The mechanical tests performed here consisted in compressing the test-pieces up to breakage point in order to draw up stress/strain curves and determine the elastic yield point, the lengthening rate, the breaking stress. A Shimadzu AGX traction-compression machine was used with a 100kN-maximum load cell under quasi-static conditions at a displacement rate of 2mm/min in the same direction as in the numerical simulations (Fig. 2). The 3 samples of test-pieces were tested. The machine was stopped as soon as the failure of the samples was seen to occur. Stress/strain curves were recorded during compression loading using Trapoziem X program. The aim was to check whether these samples remained in the domaine of linear elastic behavior when subjected to 57 MPa-compression corresponding to the pressure of 30MPa applied in the simulations with a safety factor of 1.9.

3. Results

3.1. Topology optimization simulations

Topology optimization was performed on the cube at a pressure of 30 MPa with safety coefficient of 1.9 in all the three methods of computational optimization. Fig. 3 shows the structures that were obtained.

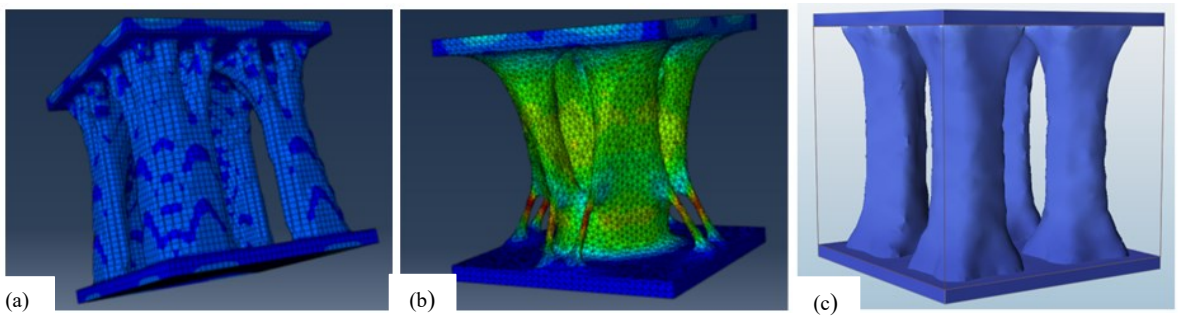

Fig. 3. Optimized structure solutions resulting from the models: (a) Abaqus DCO, (b) Abaqus SCO, (c) the Optistruct CCO.

In Abaqus SCO model, the objective function was to minimize the material weight while imposing that Von Mises stress did not exceed the elastic limit of Inconnel 718 divided by a safety factor of 1.9. penalization was performed manually with different density thresholds. Then the thresholded optimized structures were submitted to the same compression loading. Their mechanical behaviors were analyzed and compared (Table 3).

Table 3
Numerical results obtained with the Abaqus SCO model.

Density threshold	Remaining volume [mm^3]	Savings in volume [%]	Maximum von Mises stress [MPa]	Inconel 718 elastic stress [MPa]	Safety coefficient	Maximum displacement [10^{-2}mm]
0.4	1929	76	1014	980	0.96	5.2
0.3	**2115**	**74**	**522**	**980**	**1.88**	**4.6**
0.25	2238	72	447	980	2.1	4.3

The structure obtained after the manual penalization step with a threshold density value equal to 0.3 gave the best trade-off between savings in material and a safety factor of 1.9.

In the Optistruct CCO model, the objective was to minimize the strain energy while imposing as a constraint a given percentage of volume to be conserved. As shown in Table 4, among the different imposed volume percentages, the best compromise between savings in material and mechanical resistance was obtained by imposing the requirement that 25% of the material should be conserved. This configuration, where the maximum Von Mises stress was equal to 503 Mpa, enabled us to meet the a safety coefficient of 1.9.

Table 4
Numerical results obtained with the Optistruct CCO model.

Minimum volume to be conserved [%]	Remaining volume [mm^3]	Savings in volume [%]	Maximum von Mises stress [MPa]	Inconel 718 elastic yield stress [MPa]	Safety coefficient	Maximum displacement [10^{-2}mm]
40	3789	52	311	980	3.15	1.7
30	2924	63	344	980	2.8	2.6
25	**2479**	**69**	**503**	**980**	**1.9**	**3.1**
20	2086	74	656	980	1.5	4.2
15	1759	78	896	980	1.1	6.3

In Abaqus DCO, the same optimization criteria as in Optistruct CCO, were used, except the local density variables which were equal to 0 or 1. Here again, the remaining volume of 25% was compatible with a safety coefficient of 1.9. The results obtained with Abaqus DCO are summarised in Table 5 below.

Table 5
Numerical results obtained with the Abaqus DCO model.

Minimum volume to be conserved [%]	Remaining volume [mm^3]	Savings in volume [%]	Maximum von Mises stress [MPa]	Inconel 718 elastic yield stress [MPa]	Safety coefficient	Maximum displacement [10^{-2}mm]
40	4605	43	170	980	5.7	1.7
30	3767	53	252	980	3.8	2.5
25	**3148**	**61**	**503**	**980**	**1.9**	**3.9**
20	2721	66	747	980	1.3	6.1
15	2091	74	1829	980	0.5	18.3

The numerical solutions giving the best trade-off are compared in Table 6 between the three optimization models. The stress and the displacement are similar in all three cases, whereas the savings achieved in the volume differ from one model to another. The Abaqus SCO model gives the largest savings (74%), followed by Optistruct CCO (69%) and Abaqus DCO (61%).

Table 6
Comparisons between the results obtained with the three topology optimization models.

	Minimum volume to be conserved [%]	Remaining volume [mm^3]	Savings in volume [%]	Maximum von Mises stress [MPa]	Inconel 718 elastic yield stress [MPa]	Safety coefficient	Maximum displacement [10^{-2}mm]
Abaqus SCO	**-**	**2115**	**74**	**522**	**980**	**1.88**	**4.6**
Abaqus DCO	25	3148	61	503	980	1.9	3.9
Optistruct CCO	25	2497	69	503	980	1.9	3.1

The results show that all the three models are valid mechanically because they were compatible with the safety factor targeted. The authors can note that Abaqus SCO model is more performant in terms of the amount of material saved than the Abaqus DCO of about 21% and than the Optistruct CCO of about 7%.

3.2. Porosity analyses on samples obtained using laser sintering methods

The samples that were manufactured by SLM from the solutions of the three optimization approches are presented in Fig. 4.

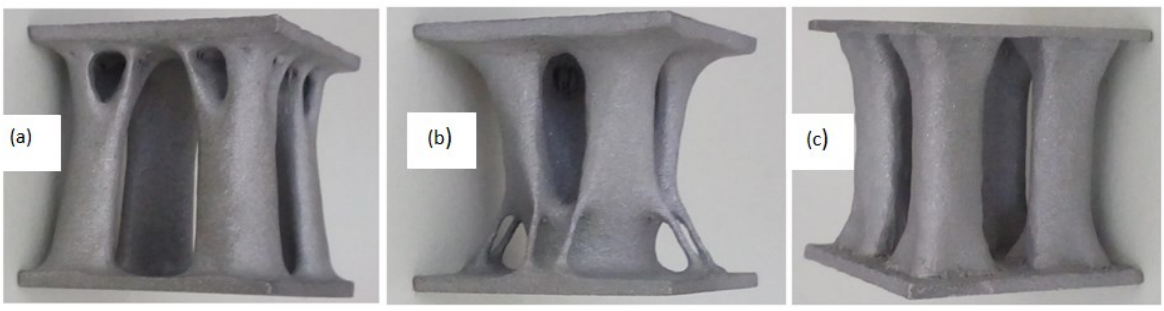

Fig. 4. SLM-manufactured optimized structures: (a) Sample based on Abaqus DCO, (b) Sample based on Abaqus SCO, (c) Sample based on Optistruct CCO.

To analyze the influence of SLM manufacturing on the microstructure of the samples, the authors studied their surface porosity, based on ten photos (1cm x10cm, Scale: 100 microns) taken with a light microscope at various points on the surface of each test-piece. Using the ImageJ software (Fig. 5), a

mean relative density of 98% was measured (Table 7). This high density obtained by SLM manufacturing validates the test-pieces to be tested mechanically.

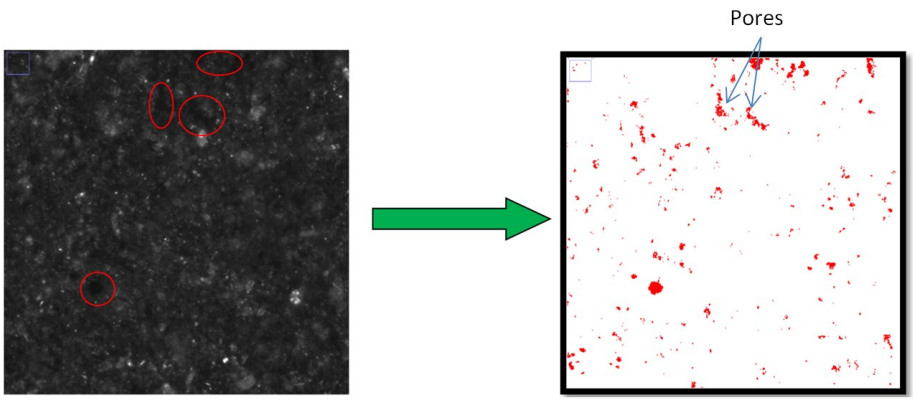

Fig. 5. Pore analysis at the surface of the test-piece. The surface area which was scanned is 3.8 x 3.8 mm.

Table 7
Examples of relative density calculated on a few photos.

	Total pore area [µm^2]	Mean pore area [µm^2]	Total area of the sample [µm^2]	Percentage area of pores present in the total area [%]
Photo 1	313,903	724	1,466,834	2.14
Photo 2	247,538	574	1,456,107	1.70
Photo 3	401,697	1171	1,466,046	2.74
Photo 4	326,422	722	1,419,226	2.23
Photo 5	256,969	767	1,468,396	1.75

3.3. Mechanical behavior of the samples produced

To check the validity of the numerical findings in terms of the mechanical behavior of the components, quasi-static experimental compression tests were conducted on the three samples corresponding to the three numerical models tested. A test-piece undergoing a compression test is shown in Fig. 6.

Fig. 6. Position of a sample during a compression test.

Stress/strain curves were drawn up during the compression tests. The mean compression behaviors of the three samples are presented in Fig. 7.

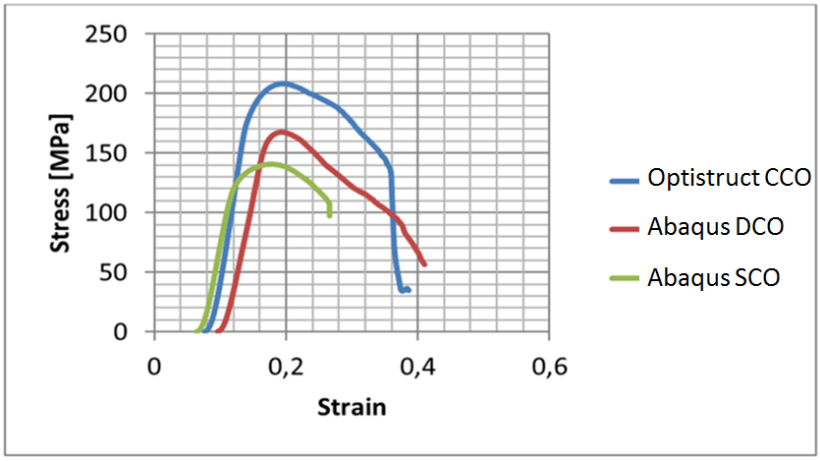

Fig. 7. Compression curves corresponding to each of the three topology optimization simulations tested.

The **linear/straight** part of the curves shows that all three optimized samples continued to show elastic behavior up to overall compression loads of 110 MPa, or even 160 MPa in the case of the Optistruct CCO model (Table 8).

Table 8
Experimental results obtained on the three optimized samples.

	Elastic yield point [MPa]	Lengthening [%]	Compressive strength [MPa]
Abaqus SCO	**110**	**0.05**	**140**
Abaqus DCO	145	0.066	168
Optistruct CCO	160	0.057	210

These experimental results show that all the three optimization simulations met the specifications defined in this study, i.e., the samples continued to show elastic behavior up to a maximum compression load of 57MPa (30MPa multiplied by a safety factor of 1.9). The experimental data obtained confirm the validity of the three numerical models tested. It is worth noting in addition that the use of the Optistruct CCO model yielded better mechanical performances than that of Abaqus DCO & SCO models in terms of the elastic yield point and the maximum stress resistance. However, analysis of the structure during the compression test showed that in the case of the Optistruct CCO simulation, cracks developed at an early stage in the plates at the top and bottom of the samples (Fig. 8). Although these cracks did not directly affect the mechanical behavior of the Optistruct samples during the compression tests, the presence of these defects shows that the topology optimization procedure was carried out differently with this model from the Abaqus DCO & SCO simulations.

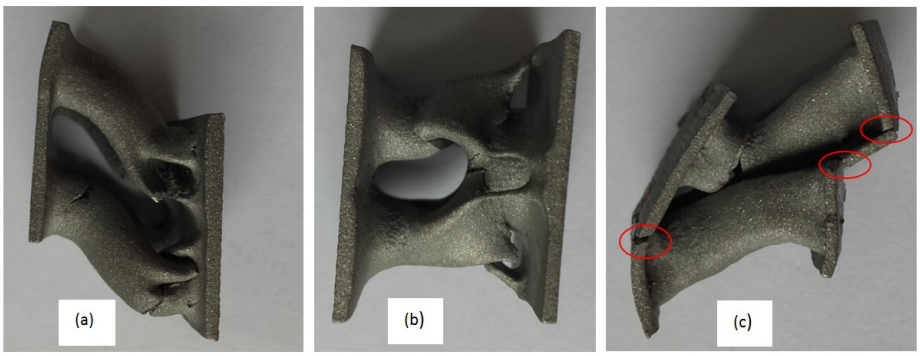

Fig. 8. Samples after the compression tests: (a) Abaqus DCO, (b) Abaqus SCO, (c) Optistruct CCO.

Since the samples obtained using all three optimization methods showed the required mechanical stress resistance, comparisons were performed taking the savings in the volume as a criterion. Based on this criterion, the approach based on the Abaqus SCO resulted in the greatest volume savings, amounting to

74% of the initial volume. The Abaqus SCO model therefore gave the best performances of the three models tested.

4. Discussion

Previous studies [33,34,35] combined topology optimization simulations with additive manufacturing methods as a means of producing lightweight parts for direct industrial applications. The aim of the present study was rather to test and compare the validity of three engineering approaches from the topology optimization computations to the SLM manufacturing.

4.1. Quality of samples produced by SLM

Most of the studies quoted in the Introduction aimed to optimize SLM parameters (laser, system and environment) in order to obtain relative densities of approximately 100%. The mechanical behavior of structures produced using SLM methods depends strongly on the relative density. Casilano & al. [14] have established, for example, that mechanical properties such as the hardness, the lengthening, the elastic yield point and the breaking stress are proportional to the relative density of the samples produced using this procedure. These authors reported that a relative density of about 99% gives products of a similar mechanical quality to that obtained using classical manufacturing procedures. In the present study, a close analysis of the surface of the samples showed that the porosity was approximately 98%, which can be said to be a highly satisfactory value. In addition, the excellent mechanical resistance of the samples subjected to compression tests also shows that the parameters of laser sintering process used in this study are suitable and give high-quality products.

4.2. Comparisons between numerical and experimental results

The levels of mechanical resistance observed in the experimental compression tests were higher than those predicted in the topology optimization calculations. Indeed, the samples showed a real elastic yield point ranging between 110 MPa and 160 MPa depending on the optimization model used, although they were designed a priori with just enough material to withstand compression loads of 57 MPa (corresponding to 30 MPa multiplied by a safety factor of 1.9). The difference between experimental strength compared with the one predicted, indicates that topology optimization computations overestimates the effect of mechanical loading. This is due to the fact optimization is based on local criteria while the experimental mechanical tests do not inspect the internal behavior of the structure but measure a global behavior which averages local events. Indeed, in topology optimization computations, the local stress occurring throughout the structure should not go beyond 500 MPa (corresponding to the elastic yield point of the Inconel 718 divided by the safety factor). In addition, in the computations, no plastic relaxation was considered and local maximal stress remained. On the contrary, during the mechanical compression tests performed on the samples, the elastic yield point may have been reached locally without affecting the overall elastic behavior before the structure's apparent plasticity threshold had been reached. Such plastic micro-deformations result in local stress relaxation without noticeably affecting the overall mechanical strength of the structure. Moreover, since topology optimization are performed at the level of the meshing elements, the quality of the meshing may affect the results of the optimization procedure. Indeed, distorted elements are liable to undergo sharply increasing stress levels. In the present study, because the cube is a regular shape, no meshing problems arose, however.

4.3. Modes of rupture observed, depending on the optimization model

The mechanical tests led on Optistruct CCO sample showed that cracks developed at an early stage in the plates of the top and bottom of the samples. These plates, which were 1mm thick, constituted non-optimized zones. The Optistruct optimization was conducted on all the rest of the structure without increasing the thickness of these plates. On the contrary, Abaqus SCO & DCO models took these rather thin parts into account and added material to reinforce them. It can be seen in Figs. 3,4 and 8 that these plates have become thicker in the Abaqus solutions. This difference in the thickness of the plates may explain why cracks developed at an early stage in Optistruct structure and not in Abaqus structures. The Abaqus DCO and Optistruct CCO solutions showed a shearing deformation, while Abaqus SCO showed axial deformation.

4.4. Comparison between the three topology optimization approaches for SLM manufacturing

The authors tested pragmatically three engineering methods of smart design, from the topology optimization computations to the SLM manufacturing. Abaqus SCO procedure gave after SLM manufacturing a mechanical structure that met the mechanical criteria and possessed the best compromise between strength versus weight. This model of optimization which allows a large flexibility in defining the design problem requires some time of computation, about 50 cycles of optimization before to converge. Moreover, several simulations were launched to test the effect of manual penalization choosing the final density threshold. Nonetheless it worth to notice that the threshold value of 0.3 which is the one proposed by default in Abaqus gave the best solution. In contrast, Optistruct CCO and Abaqus DCO require less time of computation, 3 times less time in case of Abaqus DCO. Nonetheless, if the SLM-manufactured CCO and DCO structures fitted the mechanical requirement, they show lower performance in the compromise between strength and weight. Moreover, to find this compromise via CCO and DCO methods, it is needed to launch several simulations with different percentages of weight to be conserved. Indeed, the weight to be conserved is not a result but a constraint that is imposed at the beginning. This fumbling may be time consuming and may decrease the supposed efficiency of this method compared to the SCO one. In addition, there is not any warranty about the final strength of the structure since it is only viewed as a function to be maximized. The CCO and DCO methods can be used by engineers who rapidly want to obtain a suitable design for SLM manufacturing without looking for the best compromise. On the opposite, in some critical cases, when the best compromise is wanted and the computation time is not a limit, SCO method should be privileged.

5. Conclusions

In additive manufacturing industry, it is always necessary to reduce melting time and so the amount of material to be fused which is needed while ensuring the mechanical resistance of the parts. Combining topology optimization methods with laser fusion production methods could provide a rational tool for obtaining mechanical parts in which the compromise between mechanical strength and material savings is achieved. The results of the present study confirm the validity of a design approach based on industrial calculation codes for topology optimization to manufacture resistant structures by SLM methods. In the case tested here, the aim was to identify a software program and a numerical topology optimization model giving the most satisfactory performances in terms of the mechanical behavior and material savings. To test the validity of the predictions of the numerical optimization models, physical structures were produced based on these solutions and tested mechanically. Although the three optimizations model used here all resulted in mechanically valid parts, the stress-constrained optimization performed on DS Simulia Abaqus code gave the best material saving. This method consisted in minimizing the volume, imposing a safety factor on the elastic limit as the main design constraint and applying a manually penalization procedure to zones with composite densities. This penalization results in structures which can be constructed physically. However, the final structure obtained does not exactly match the solution initially given by the topology optimization calculations. Introducing latticed structures with adaptive thicknesses into the calculation codes should make it possible to simulate the low-density zones which contribute to the overall mechanical behavior of a structure. It will result in reducing even more the material amount needed with optimum mechanical behavior.

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