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Selective laser melting (SLM) and topology optimization for lighter aerospace componentes

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Abstract

Additive Manufacturing (AM) is a manufacturing process through which a 3D component is produced by consecutively adding material. One of the most promising AM processes is SLM. In SLM a laser completely melts metallic powder particles together forming a 3D component. SLM is known for its freedom of manufacturing constraints allowing complex geometries and high material efficiency. Topology Optimisation (TO) is an optimisation type that calculates the optimal material distribution for a given problem. The combination of SLM with TO is being developed to create lightweight components. In this work, the whole development process, from optimisation to design, production and testing is addressed. Initially, an aircraft bracket topology was optimised to be produced by means of SLM. The TO solution was interpreted and designed for AM. During the interpretation and design process, a design methodology was defined in order to facilitate and make more accurate the TO solution design and make it ready for AM. After the optimised component was produced, metrological and mechanical tests were performed in order to validate the final design and the computer analysis. The optimised component showed considerable weight reduction with an increase of the factor of safety. The experimental tests revealed a good relation to the computer analysis evidencing, however, room for improvement, both in the computer model and the experimental tests.

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Keywords: Additive Manufacturing (AM); Selective Laser Melting (SLM); Topology Optimisation; Design for AM; Experimental testing.

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1. Introduction

Additve Manufacturing (AM) [Gibson et al. (2010)] is a process of manufacture through which an object is built by material addition in layers. Inside AM's metal methods, SLM is one of the most promising ones. SLM is the process through which a laser selectively melts particles of metal powder together, in layers, until a 3D object is created, being possible to produce complex geometries and relative densities close to 100% [Aliakbari (2012)]. However, SLM also has specific issues which need to be well understood in order to use its full potential [Kruth et al. (2010), Vandenbroucke et al. (2007), Song et al. (2014)].

TO [Bensoe et al. (2003)] is a structural optimisation method that calculates the optimal material distribution inside a design domain for a given problem. Conventional manufacturing processes often struggle or even fail to accomplish the designs that result from the use of TO, due to its complex geometries and shapes [Zhou et al. (2002)]. On the other hand, SLM, for its freedom of geometries and lack of manufacture constraints, is a particularly suited manufacturing process for the TO design. There have been several authors combining the use of TO with SLM with the objective of making the most of both technologies [Muir (2013), Emmelmann et al. (2011), Tomlin et al. 2011)].

2. Methodology

The methodology followed in this work is illustrated on Figure 1. An initial aircraft component with three static load cases was given. Figure 2 illustrates the original component.

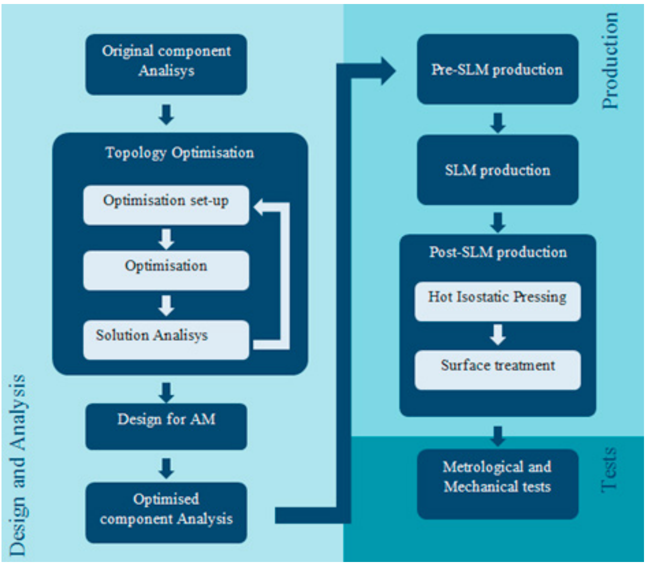

Fig. 1 – Methodology scheme.

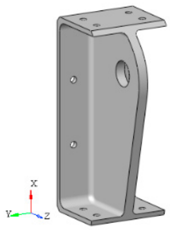

Fig. 2 – Original component.

The component is assembled on its surrounding structures by 12 rivet holes with a 4.1 mm diameter and the load is applied in the larger hole, called the load bearing lug, with a 16 mm diameter. Table 1 shows the loads of each load case.

Table 1. Load Cases.

Load Case	Load (kN)		
	F_X	F_Y	F_Z
1	5	0	-3
2	6	0	0
3	3	3	-2

The component was originally made of the aluminum alloy 7050-T7451. The goal is to reduce weight while maintaining the stress levels observed in the original component using the titanium alloy Ti6Al4V. This alloy is often used in aerospace components [Boyer (1996)]. There are several works on the mechanical properties of Ti6Al4V produced through the SLM method [Vandenbroucke et al. (2007), Hernández (2014), Qiu et al. (2013)].

The TO is an iterative process. The base optimisation set-up is defined and then the variables are adjusted until the solution fits the established goals in a preliminary analysis, such as required weight reduction or stress levels.

After the optimisation, a strategy for the solution interpretation and modelling is defined. The validation of this strategy is done by comparison of the TO solution with the optimised component design.

The optimised component final design is analysed using Finite Element Method (FEM) in order to validate stress levels and check for stress concentration regions or some need of material reinforcement.

In the Pre-Production phase the DfAM guide is created. The limitations of the SLM process are addressed in order to point out any eventual design issues with the optimised component design.

In the production phase, the optimised component is produced.

After printing, the optimised component goes through a Hot Isostatic Pressing (HIP) treatment to eliminate any pores in the material and release residual stresses.

For the metrological test, the final component is scanned and the produced component is compared to the original design. For the mechanical tests, there are two main strategies which need to be well defined. The first is how to replicate accurately the load cases. The second is the definition of the data that will be gathered from the tests to compare with the Finite Element (FE) model and how is this data going to be gathered.

3 Results and discussion

3.1 Topology Optimisation

In this work there were several inputs for the TO that had to be defined in order to achieve the optimal solution. The optimisation inputs were:

- Design Domain
- Mesh
- Control Parameters
- Objective
- Constraints

The design domain influences the range of topologies available for the optimisation solution. A larger design domain allows more material distributions. The larger the design domain, the more finite elements are used in the optimisation increasing significantly computing time. The used approach was to start from the original fitting domain and tune the optimisation mesh and control parameters, this way less computing time was needed for these parameters convergence study. After the previous parameters were established, a new initial design domain was defined in order to allow more topologies then the initial one.

The mesh has great influence in the final solution. Highly refined meshes give very different topologies from less refined meshes. In the final design domain, a more controlled method for meshing was used in order to ensure its high quality.

The control parameters also have great influence not only in the solution convergence degree, but also in the computing time, thus a convergence study on these parameters was run. In this optimisation there were two control parameters which were studied, the Relative Convergence Criterion (RCC) and the Discreteness Parameter (DP) which is the equivalent for penalty factor in TO theory.

The objective function was the weighted compliance in order to consider the three load cases in the topology optimisation [HyperWorks Guide]. This response is given by Equation 1

$$C_w = \sum w_i C_i \tag{1}$$

where w_i is the weight and C_i is the compliance of load case i which is given by Equation 2

$$C_i = \frac{1}{2} u_i^T f_i \tag{2}$$

where u_i and f_i are the displacement and force vectors, respectively, corresponding to load case i.

The objective was the minimization of the weighted compliance and each load case was given the same weight.

There were two constraints defined in the optimisation. The first one was regarding the volume fraction of the design domain. The second was a symmetry constraint, forcing the optimised solution to be symmetric with respect to the component's mid vertical plane as the original component is. Figure 3 and Figure 4 illustrate the TO boundary conditions and final solution pseudo-density distribution.

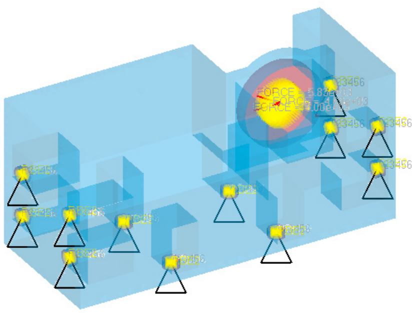

Fig. 3 – Final Design Domain (blue) and boundary conditions.

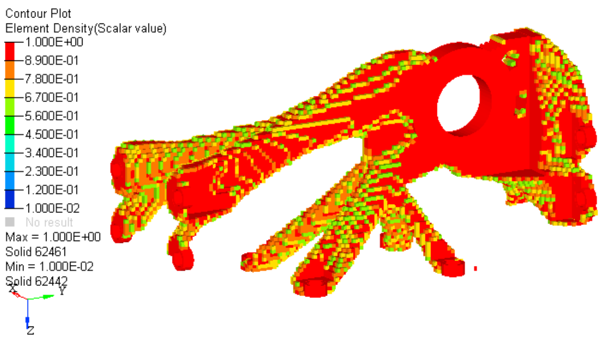

Fig. 4 – TO solution with element pseudo-density distribution.

3.2 Design and Analysis

A methodology was defined to address the conversion from the topology optimization solution to the optimized component final design. In order to achieve the organic shape of the topology optimization (TO) solution, a freeform surface modelling was used option for the optimized component design.

The design strategy followed two steps. The first step was the design of the non-design regions. The second step was the design of the remaining component by connecting the non-design regions respecting the TO solution. Figures 5, 6, and 7 illustrate the FEM analysis meshes and the stress distribution for each component.

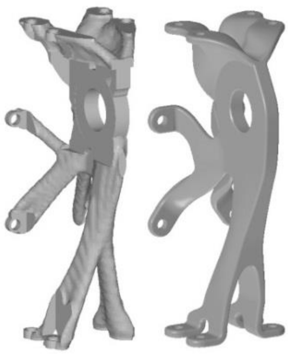

Fig. 5 – TO solution (left) and optimized component final design (right).

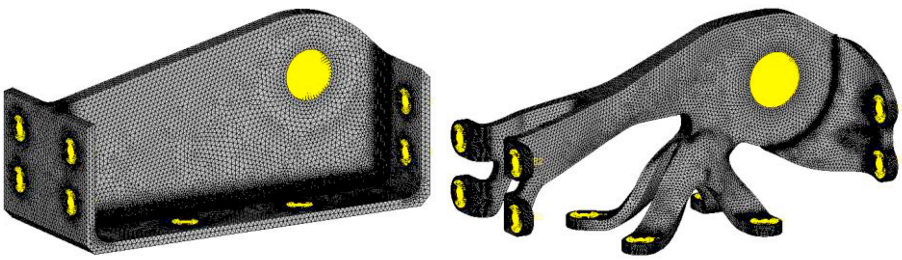

Fig. 6 – Mesh of the original component (left) and the optimized component (right).

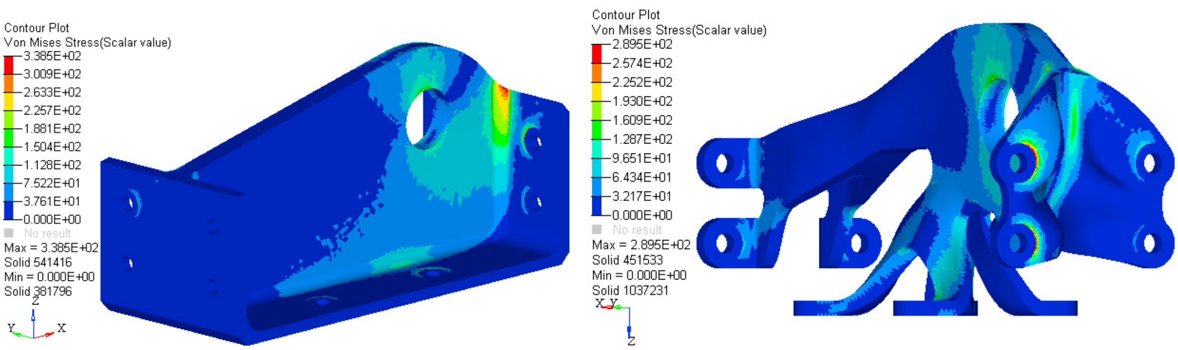

Fig. 7 – Stress distribution of the original component (left) and the optimized component (right) for Load Case 3.

3.3 Design for Additive Manufacturing and Production

Even though AM opens up a new range of design possibilities, it also has its own limitations that must be taken in consideration during a component design. Inside AM, SLM has its specific limitations because of its high temperature gradients. In this section, four manufacturing issues were defined:

- Process accuracy [Vandenbroucke et al. (2007), Wang et al. (2013)]
- Supports [Vandenbroucke et al. (2007), Hussein et al. (2013), Jhabvala et al. (2012), Wang et al. (2013)]
- Surface Roughness [Vandenbroucke et al. (2007)]
- Geometrical feasibility and possibilities [Ponche et al. (2012), Vayre et al. (2012)]

The machine SLM® 125 HL from SLM Solutions GmbH was used to produce the final component. Figure 8 illustrates the manufactured component.

Fig. 8 – Optimised component manufactured.

3.4 Tests

The metrological test was done using 3D scanning, see Figure 9. The machine used was the Comet L3D from Steinbichler. The scanned image, saved in STL format, was then compared with the original STL used for the component's production. The deviation goes up to 0.8 mm in some areas of the component. This deviation is related with the SLM process itself. The high temperature gradients present during the manufacturing of the component leave residual stresses in the material which, in worst cases, can even rip some supports away from the platform.

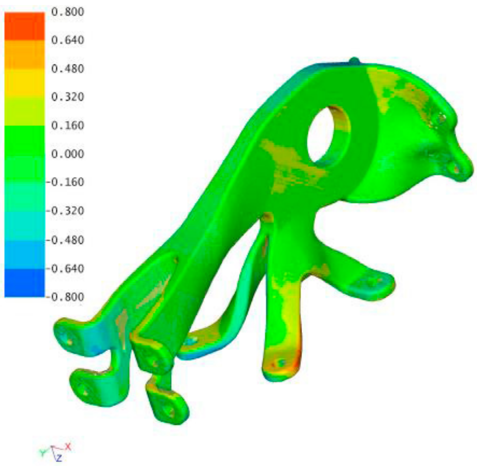

Fig. 9 – Metrological test result. Deviations in mm.

The mechanical tests were done with an Instron 3669 machine. In order to replicate the load cases in the machine, an interface set-up was designed and manufactured. Figure 10 illustrates the tests set-up for Load Case 2. Table 2 shows the comparison between the results obtained with FEM and experimental tests.

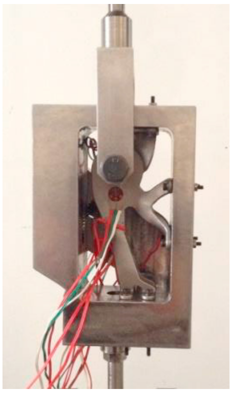

Fig. 10 – Mechanical tests set-up for Loading Case 2.

Table 2 – Mechanical tests results for Load Case 2. The design load was applied. The strain values are in μm/m.

Sensor	R1 ε_{Max}	R1 ε_{Min}	G3	G4	G5	R6 ε_{Max}	R6 ε_{Min}
Strain - FEM (Design Load)	271	-292	94	170	402	254	-85
Strain - Mech. tests	297	-139	-99	245	475	239	-128
Δ (%)	10	-53	-205	45	18	-6	50

4. Conclusions

The TO was successfully implemented and proved to be an effective way of taking advantage of the manufacturing freedom provided by SLM. It was possible to decrease the material volume of the original component by 54%, resulting on a 28% weight reduction motivated by the change in material from aluminum to a titanium alloy. Also because of the change of material, the factor of safety increased by two times the original value.

A fair reproduction of the problem's Loading Cases was made. In LC2 there were good approximations of the maximum principal strain in four different points of the component suggesting a good relation between the FE model and the produced component. Loading Cases 1 and 3 were more influenced from the simplifications of the FE model, namely the isotropy and the boundary conditions.

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