Metal Additive manufacturing:
a breakthrough in the designing processes
of lightweight aeronautic parts

Introduction

The technology breakthrough given by the metal Additive Manufacturing (AM) revolutionizes the designing process of manufactured parts, as well. This layer-by-layer technology with laser beam consolidation allows to manufacture complex metal parts directly such has turbine blades or compressor blisks. More generally, many existing parts made of an assembly of several components can be re-design in order to replace assemblies to single part and to re-integrate the making part into the existing structure. This requires the precise elaboration of the functional surfaces in dimension and space. The re-designing process is usually associated with topology optimization to minimize the weight of the part while complying with the mechanical properties. To illustrate that point, the re-designing methodology of a landing gear, a part involved in the input/output mechanism of the aircraft wheels during landing, is described. This study is related to the project of the association Replic'air to make the DEWOITINE D551 aircraft (figure 1) reviving using new technologies such as laser cutting and additive manufacturing.

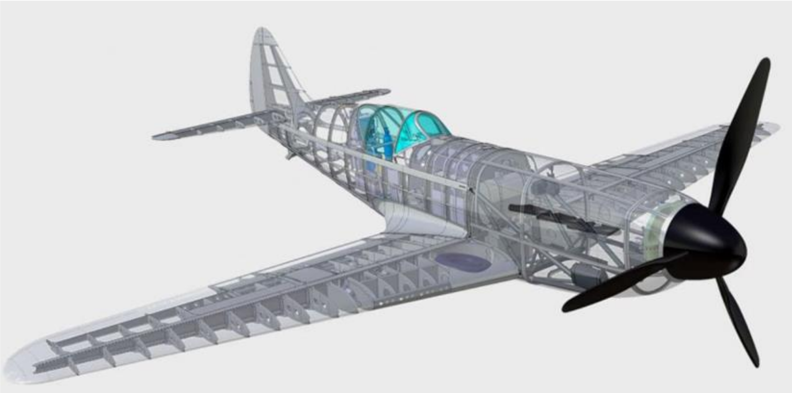
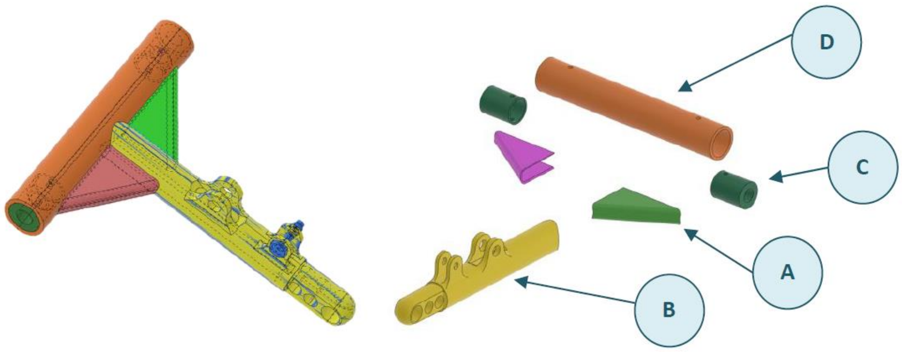


Figure 1: 3D model of the DEWOITINE D551 fighter aircraft, after its inventor name, and constructed in 1940.

Objective of part integration

The original landing gear was designed in 1951 by the inventors of the DEWOITINE aircraft. This small but relatively complex part was composed of several elements (see caption of figure 2) mechanically welded. They were made using conventional processes: sheet metal working for gussets, tube cutting for the support, machining (5 components) and welding for the crossbar. The overall elements were assembled through riveting and welding. The objective is thus to integrate the 4 parts (A+2xB+D) into a single one taking also advantage of the AM to optimize the strength to weight ratio during the part re-design.



Pieces	Name	Number	Mass (g)
A	Gusset	2	46
B	Crossbar	1	219
C	Trunnion arm	2	71
D	Support	1	199
A+2B+D	4 part assembly	1	510

Figure 2 : 3D model of the original landing gear of the DEWOITINE D551 constituted of several components. The additive manufactured part will have to integrate 4 components in one part with a weight lower than 510 g.

Design space definition as the starting point of strength to weight ratio optimization

Since the topology optimization is based on mass removal while complying the mechanical properties, the design space has to be large enough around the functional surfaces to yield such target. Figure 3A shows that design space including the original landing gear, with the functional surfaces colored in blue. These surfaces have to be precisely dimensioned in size, shape, and volume space. Nevertheless, a connecting rod crossing nearby the landing gear (see figure 3B) means that this optimum design space has to be restricted with respect to symmetry as shown in figure 3C. This design space corresponds to an overall volume of 239 cm^3 that is a mass of 5.80 kg. (assuming Inox 316L as material).


A B C

Figure 3: Definition of the design space as the starting point of the topology optimization of the landing gear. A, optimal design space; B, space constraint by the presence of a connecting rod; C, optimal constraint design space.

Choice of candidate materials

As the topology optimization is conducted through higher strength to weight ratio, the candidate materials could be characterized either by high mechanical performances but relatively high density or either low density but poor mechanical performances. The Inox steel 316L is thus a good candidate thanks to its high tensile strength (R_m(max)=704 MPa) and high yield strength ($R_{p0.2}$(max)=511 MPa) that have been characterized on testing specimens obtained from AM technology LBM. On the opposite, aluminum alloys are interesting thanks to their low de density (2.7 g/cm^3) three times lower than steel density (7.9 g/cm^3), while their R_m(max) and $R_{p0.2}$(max) mechanical characteristics are about twice lower.

Mechanical loading for topology optimization and final numerical validation.

Landing gear is a heavily loaded part during the input/output mechanism of wheels, through the functional surfaces which assemble the part onto other parts of the aircraft and transmit mechanical load. Thus several mechanical tests have been considered such as bending, compression and torsion tests which are listed in table 1 and illustrated in figure 4A. The mechanical load is a force applied on the bores of the functional surfaces of the part, some zones being blocked. In the case of computing optimization, these forces and blocked points are distributed on the discretization nodes of the bores of the functional surfaces (colored zone of figure 4B).

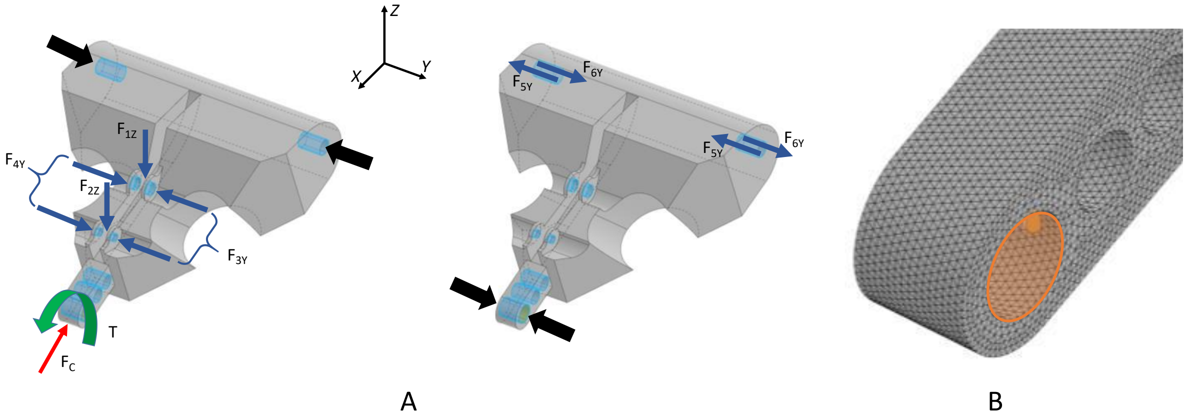


Figure 4 : A; Description of the different mechanical tests carried out to characterise the landing gear.

➡ *Blocked points;* ➡ *Bending forces;* ➡ *Compression force;* ➡ *Torsion couple*

Numerically, the applied forces, couple and fixed points are distributed on the discretisation nodes of the bores as indicated in B through the orange zone.

B; tetrahedral mesh discretisation for the Finite Element Method used to calculate mechanical properties.

Applied loading case	Effort type	direction	Intensity (N)
1	Bending - F_{1Z}	-z	6 500
2	Bending - F_{2Z}	-z	3 000
3	Compression - F_C	-x	28 000
4	Lateral bending - F_{3Z}	-y	500
5	Lateral bending - F_{4Z}	y	500
6	Lateral bending- F_{5Z}	-y	500
7	Lateral bending- F_{6Z}	y	500
8	Torsion - T	Counter clockwise	30 N.m

Table 1: Mechanical loading tests used for topology optimization and numerical validation of the additive manufactured part.

Two-step methodology for the topology optimization

The objective of the optimization is to minimize the volume (or mass) and layout of the part while maximizing a specific mechanical characteristic, here the stiffness, for the eight sets of loads (see table 1). This is done in two steps described below.

- Step 1: Optimized rough skeleton through stiffness criterion

This optimization is done automatically under symmetry constraint, through an iterative process until the stiffness no longer complies. Note that the finite element analysis of stiffness was conducted using the elastic constants (Young's modulus and Poisson's coefficient) of material specimens elaborated using additive manufacturing. As a result, a rough skeleton is obtained representing the effort pathways and minimal thickness (figure 5). As regards the candidate materials, aluminum part gives rise to an increase of 17% of weight compared to the original one whereas steel part gives rise to a weight loss of -17%. Obviously, steel as material is the best candidate.

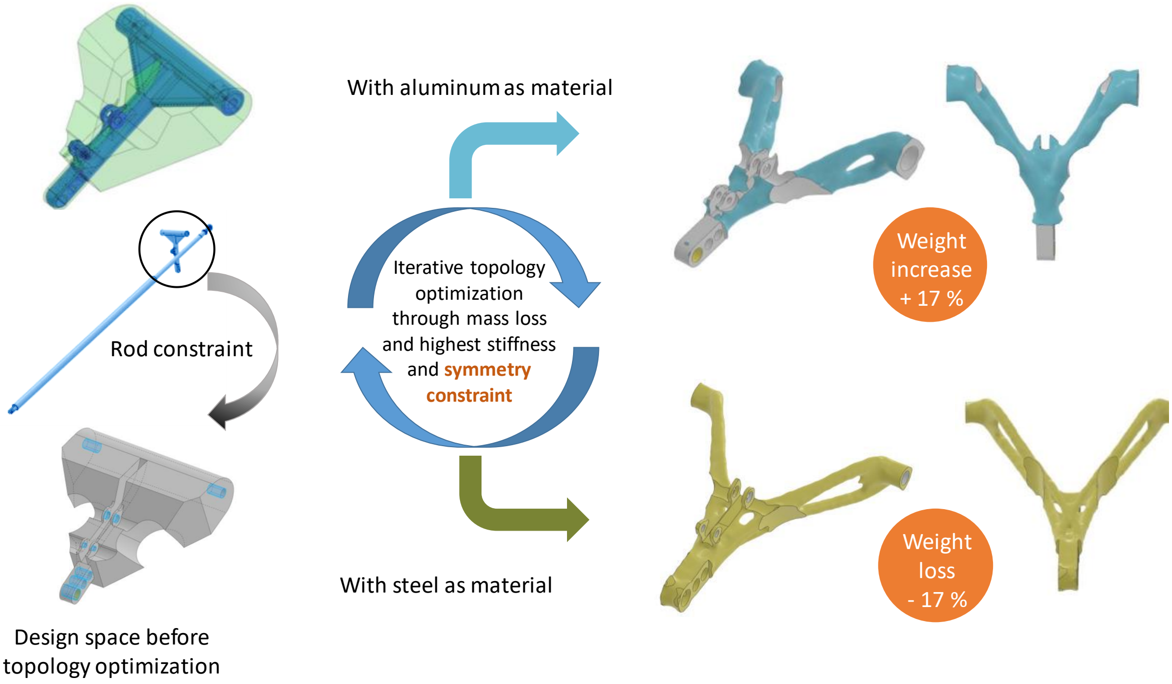


Figure 5: First step of the topology optimization: from design space to optimized rough skeleton through stiffness criterion.

- Step 2 : Final re-designing step

The rough shape obtained for steel as material is now a guideline to re-design the part with respect to the precise location of the functional zones, the regularity of the surface and the additive manufacturing constraints regarding the limitation of the production supports used to prevent overhanging regions. This re-designing part is shown in figure 6 and slightly deviates from initial skeleton, especially for weight loss compared to the original part which is now reduced to -9 %.

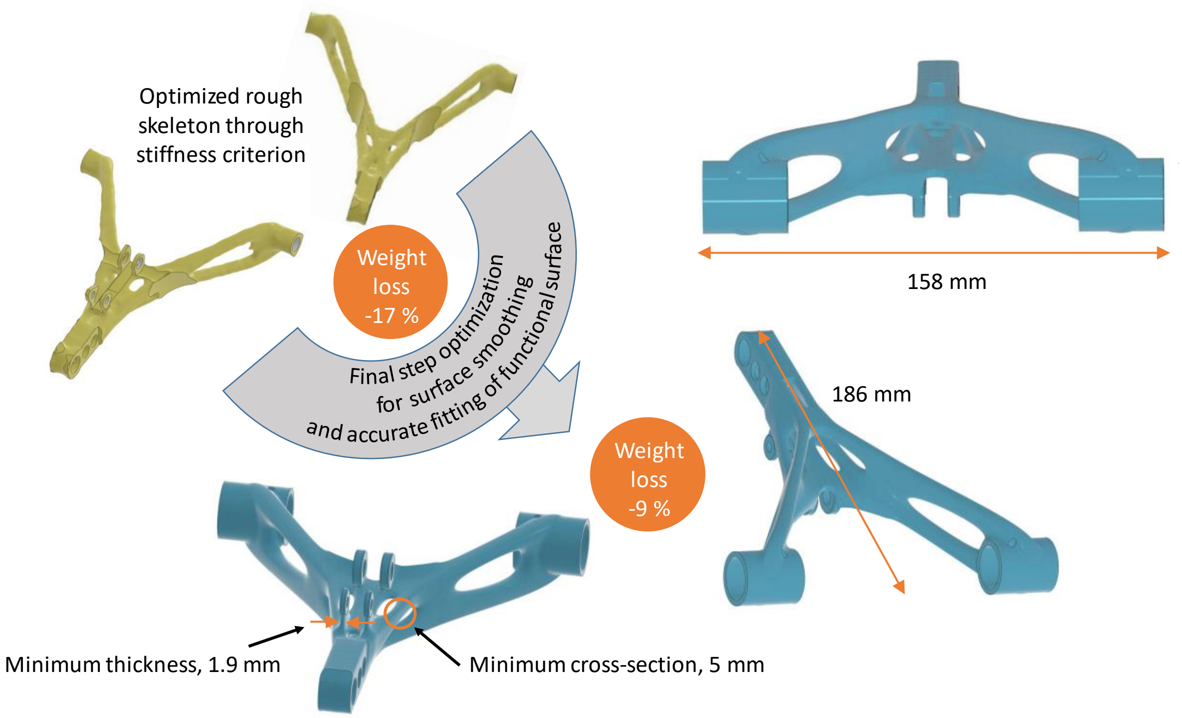


Figure 6: Second step of topology optimization: from the optimized rough skeleton to the final design of the landing gear.

Numerical validation of the final designed landing gear

The final part obtained after the two-step topology optimization is numerically validates through finite element analysis of Von Mises stress, minor and major principal stresses (usual stress criterion for material failure) for the eight sets of loads (see table 1). Except for the two bending loads in the z-direction (cases 1 and 2), all the other sets of load cases give rise to stress field values more than three times lower than the allowable stresses. For the two bending loads in the z-direction, the most critical allowable to applied stress ratios decrease to about 1.5 for most of the three types of stresses (Table 2). As regards the stress fields shown in figure 7, these critical values, for von Mises and major principal stresses, are located on the lower branches nearby the place where the trunnion arms will be positioned (see Figures 7A and 7C). For the minor principal stress, the minimum value is located at the blocked zone of the bending test (figure 7B).

Applied load case	Von Mises stress	Minor principal stress	Major principal stress
1	1,54	1,41	1,62
2	1,56	1,41	2,38

Table 2 : The most critical values of the allowable stress to applied stress ratio obtained for the two z-direction bending loads (see table 1).

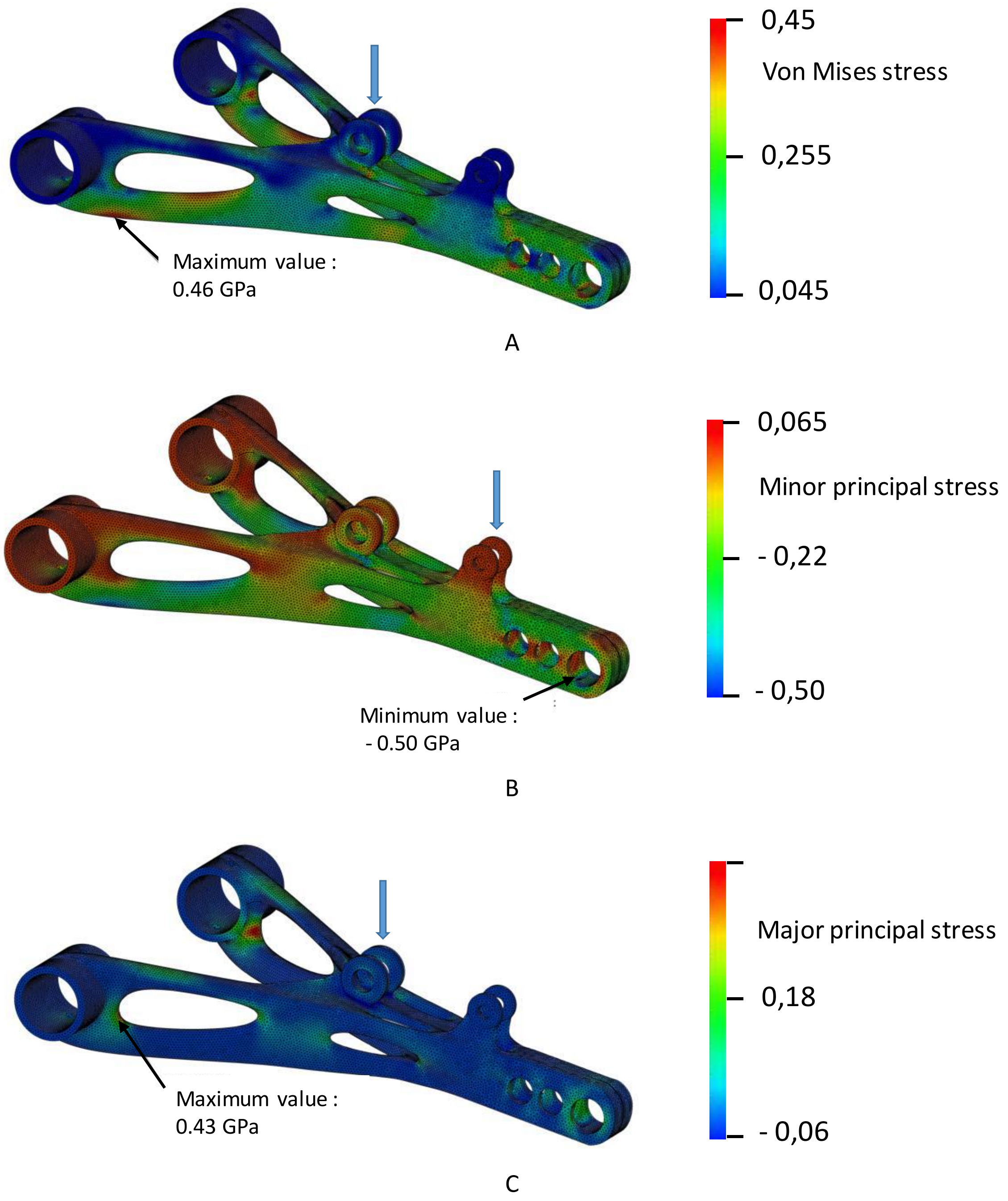


Figure 7 : Finite element analysis of the Von Mises stress (A), minor (B) and major (C) stresses for z-direction bending loads. The arrow indicates the location of the applied force.

Conclusion

Through the re-designing process of a former landing gear, is highlighted the advantages that offer the additive manufacturing, first to replace assemblies into single or less numerous parts integrating functional surfaces as well, and secondly to optimize geometries with the best strength to weight ratio. After design validation, which was the final point here, it is then possible to move to prototyping phase to corroborate additive manufacturing feasibility. With the landing gear design that is proposed here, it could be possible to manufacture seven specimens with the same production batch using the LBM (Laser Beam melting) technology.