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A DESIGN FOR ADDITIVE MANUFACTURING METHOD OF DIRECT METAL PARTS FOR AEROSPACE APPLICATIONS

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Abstract. *In the aerospace industry, the additive manufacturing process for metal parts shows a huge potential. However, a challenge at the same order of magnitude is due to its low technology maturity, fragmented technology approaches and lack of methodological design approach for manufacturing. These constrain severely the use of metal additive manufacturing in the aerospace industry. This work presents a design for additive manufacturing (DFAM) method of direct metal part (end use part) for aerospace application in accordance with the constraints of the laser powder bed fusion process (L-PBF) and complementary processes, such as surface finishing. The proposed DFAM method consists of the concatenated activities: part function and raw material setting, topology optimization input, setting up of functional surfaces and build-up orientation of the part, 3D modeling procedure, structural verification and manufacturing optimization, and integration of the knowledge of the L-PBF capabilities and complementary processes. A titanium airframe part was designed and manufactured to verify the proposed DFAM method: it is shown that an optimized part in terms of weight and raw material savings was successfully obtained. The part also met the aerospace requirements of smoothness and geometric uniformity. In spite of the promising outcome fully described herein, further design trials using other parts are necessary to validate fully the DFAM method, as other combinations of functional requirements and geometrical constraints may pose additional challenges.*

Keywords: *design for additive manufacturing; laser powder bed fusion; complementary processes; direct metal part; aerospace.*

1. INTRODUCTION

Design for Manufacturing (DFM) is a philosophy and mind-set in which manufacturing input is used at the earliest stages of design in order to design parts and products that can be produced more easily and more economically (Poli, 2001). There are three goals in DFM according to Xie (2002): increase the quality, decrease the cost and shorten the developing cycle time. However, Joneja (2010) stated that is essential to know the effects of design in terms of materials, geometry and tolerances on manufacturing as shown in Figure 1.

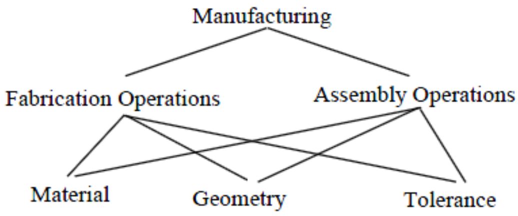


Figure 1. Effects of design (materials, geometry, tolerances) on manufacturing (Joneja, 2010).

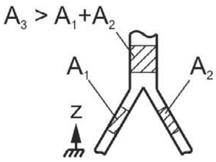
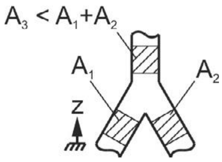
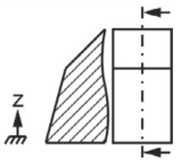
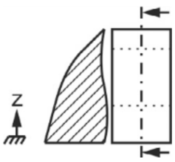
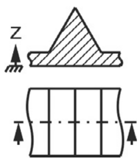
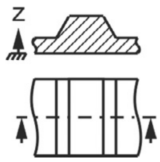
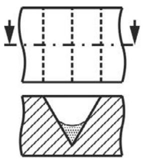
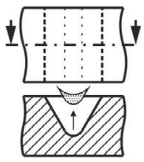
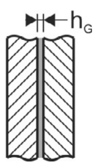
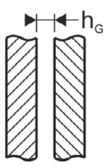
In subsequent years, the idea of DFM was extended to include other aspects of better designs including design for maintenance, design for environment, design for cost, design for technology, etc. Often, this application of concurrent engineering is referred to as DFX, where X is a variable selected from the set manufacture, assembly etc. (Joneja, 2010).

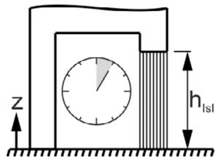
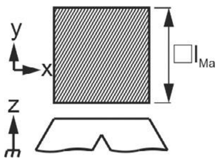
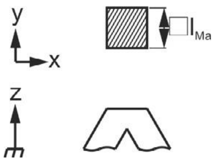
Several methods are used to design parts, which allow optimizing the part through the advantages posed by the manufacturing process. However, the possibilities offered by the innovative processes such as additive manufacturing are not fully used during the design conceptual phase. In fact, most of the parts made by additive manufacturing are often design with conventional rules used for other processes as machining, moulding, forging, etc. (Bourhis *et al*., 2014).

Thus, some researches have been conducted to propose methodologies integrating the advantages of the additive manufacturing (AM) processes during design stage. Those methodologies are called design for additive manufacturing (DFAM) according to Gibson *et al.* (2015).

Additive Manufacturing technologies create parts layer by layer. Thereby, many benefits are offered. Especially extended design freedoms provide new potentials for the design of technical parts. To make these benefits accessible, design rules for AM were developed by Adam and Zimmer (2014) for laser powder bed fusion (L-PBF) process and fused deposition modeling (FDM). The design rules are totally focused on geometry, thus they are function-independent and easily transferrable on individual part designs as shown in Table 1.

Table 1. Extract from the design rules catalog (adapted from Adam and Zimmer, 2014).

Description	Design for manufacturing	
	Unsuitable	**Suitable**
Element transitions' thicknesses should be chosen so that the cross sectional areas in the building plane remain of the same size or become smaller.		
Sharp (outer and inner) edges should be avoided. In order to receive better form accuracies edges should be rounded. The rounding radii correlate with the outer radii of simple-curved elements		
Edges that form vertical extreme points should be blunted parallel to the building plane. The dimensions of the blunted areas should be larger than non-curved elements' thicknesses.		
Inner edges should be rounded or blunted in order to simplify the removal of disperse support structures (e.g. powder).		
Minimal gap heights should be kept in order to receive small dimensional deviations and to ensure the removal of disperse support structures (e.g. powder) L-PBF: $h_G \geq 0.2$ mm		

Islands' starting positions can be chosen freely as they do not influence the building time significantly.	-	
Material accumulations should be avoided. Maximal dimensions have to be kept to receive suitable manufacturability. L-PBF: $l_{Ma} \leq 20$ mm x 20 mm		

Noorani (2006) has been presented the steps involved in product development using rapid prototyping as shown in Figure 2.

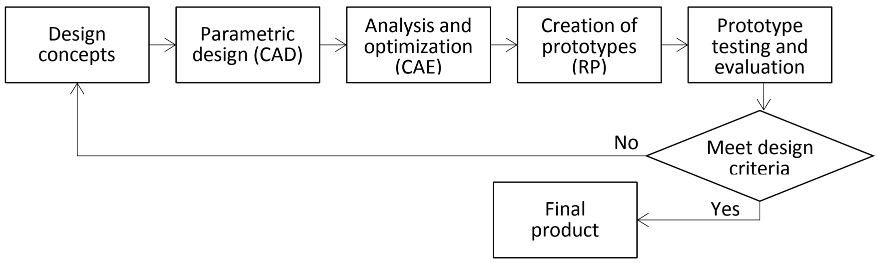


Figure 2. Product development cycle (Noorani, 2006).

This product development cycle denotes the impact of rapid prototyping on product development process. This method comprises design concepts, parametric solid modeling, analysis and optimization, rapid prototyping and testing, which must be integrated to a design and manufacturing system. Figure 2 shows this concept of the integrated product development (Noorani, 2006).

An aircraft is conceived as a complete structure, but for manufacturing purposes must be divided into sections, or main components, which are in turn split into sub-assemblies of decreasing size that are finally resolved into individual detail parts. The parts must be designed using the principles of simplicity, standardization, lightness, structural integrity, accuracy and producibility as mentioned by Niu (1995).

The AM technology has great potential to meet those principles by minimum fabricating and processing operations, mechanical simplicity and tolerances, and to overcome other, such as effective use of raw material, machining economy and weight savings enabling highly complex structures, which can still be extremely light and stable. It provides a high degree of design freedom, the optimization and integration of functional features, the manufacture of small batch sizes at reasonable unit costs and a high degree of product customization even in serial production (Gibson *et al*., 2015).

The capability of the laser powder bed fusion process (L-PBF) for titanium parts was taken into account in this work. As per ASTM F2792 (2012), L-PBF is a metal additive manufacturing process in which a digital 3D design data is used to build up a component in layers by depositing and melting material.

Thus, based on the above-mentioned references and characteristics of aerospace parts, this work proposes a design method for direct metal part to support an integrated product development, by efficiently using the geometrical freedom and raw material optimization provided by this AM technology.

2. EXPERIMENTAL PROCEDURE

The design for additive manufacturing method for aerospace application - DFAM - is proposed as per Figure 3. This comprises 3D modeling strategy and integrated product development based on a topology optimization input. The goal is a structured approach, which would help the designer to integrate the knowledge of the L-PBF process in his design to meet the requirements of direct metal part for aerospace application.

The capabilities of L-PBF, complementary processes and aerospace requirements should be taken into account to provide design guidelines for direct metal aerospace parts, whose main drives are: structural integrity, light weight and low raw material consuming. Concurrently, a smooth (continuity of curvature and tangency) and uniform (no abrupt dimensional variations) geometry for the part have to be achieved.

The first main set of the design method is an analysis of the basic function of an airframe part, which encompasses motion transmission and/or bear loads under service condition such as temperature, humidity and pressure. Additionally, parts should meet requirements of safety, service life, maintenance, maximum weight and chemical compatibility with other nearby parts. Therefore, a raw material can be selected in this step according its mechanical and chemical properties to meet requirements related to the part function.

In the second main set, the properties of the material comprise chemical, electrical, environmental, magnetic, manufacturing, mechanical and thermal properties to support the raw material selection, part design and manufacturing process parameters according to the part function. However, unlike traditional manufacturing processes, a statistical database of material processed by L-PBF and complementary processes is not yet available in international technical standards. Then, tests are required to obtain the processed material properties in order to support the design and manufacturing of the part.

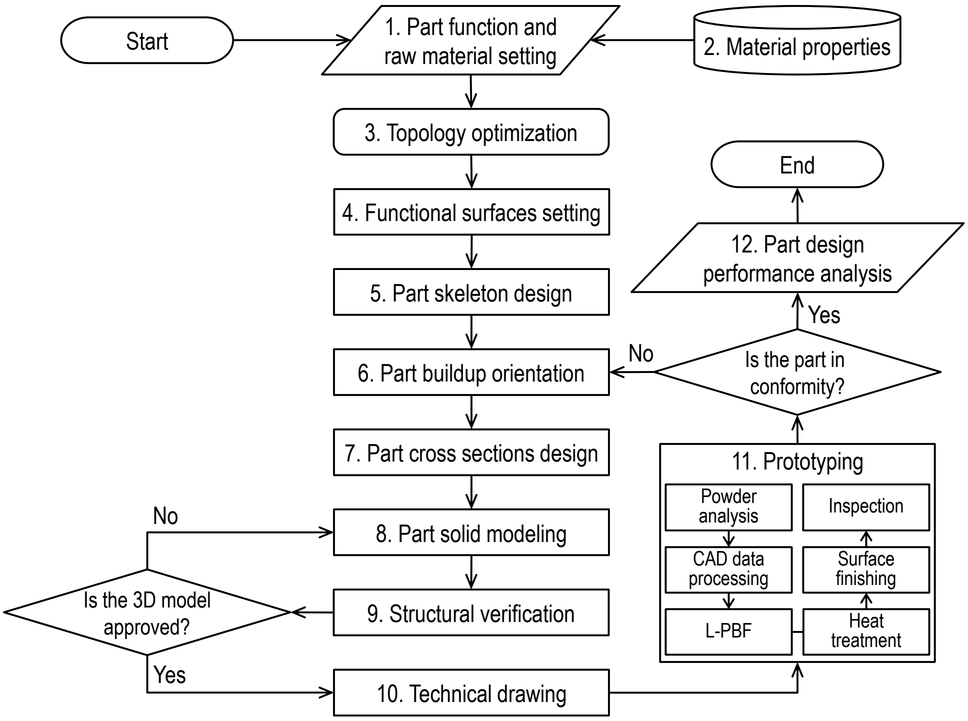


Figure 3. DFAM method of direct metal part for aerospace application.

In accordance with the third main set, a topology optimization can be performed according to the mechanical properties of the processed raw material, design space (volume to be optimized), load case and part performance requirements. This topology optimization can lead to a maximum optimization of the part geometry.

The fourth main set of the design method is an analysis of the part interfaces and setting of functional surfaces comprising dimensions, position and related tolerances in accordance with dimensional and geometrical specifications. However, it is also linked to the constraints of assembly and manufacturing of the part to be designed.

In addition, functional surface is one in which the part material interacts with the surrounding environment. These interactions can be physical, chemical, electrical, mechanical, thermal etc. The surrounding environment comprises nearby solid parts, atmospheres and fluids (Asthana, 2006).

The fifth main set allows fulfilling the dimensional and geometrical specifications in relation to the AM process capability and the finishing process characteristics. The setting of the part skeleton is conducted first, by obtaining the load path centerline of the topologically optimized geometry. Then, taking into account, the minimum build time and minimum amount of support structures, the part features orientation and cross sections are determined by extracting and treating the features cross sections of the corresponding topologically optimized geometry. Thereafter, the envelopment of the topologically optimized geometry is performed using such skeleton and cross sections as inputs to generate a smooth (continuity of curvature and tangency), uniform (no abrupt dimensional variations) and parameterized 3D geometry. Manufacturing capabilities and constraints, such as maximal and minimal dimensions, accuracy, and required accessibility for finishing operations are taken into account at this moment. During this step, the CAD system's tools for modeling curves and solids are applied. A finite element analysis is conducted for a verification of structural parts.

Once the part geometry is finally determined, detailed design including the corner radius and machining allowance can be carried out, taking into account the part classification (primary, secondary and non-structural as per Federal Aviation Administration (2007), dimensional and finishing requirements, and the finishing process capability in terms of accuracy and surface roughness. Milling, turning and drilling require at least 1 mm of machining allowance, while processes such as shot blasting, electrochemical polishing, immersed tumbling and sanding remove no more than 0.1

mm thick, wherein machining allowance is not required. In addition, throughout the design process, a structural verification is performed to validate the part geometry.

As for non-structural parts, the same process should be followed, except that there is no input from a topology optimization and the structural verification is much simpler, since these parts are not subject the static and / or dynamic loads.

Finally, the sixth main set allows fulfilling the physical and assembly requirements in relation to the capability of the L-PBF and complementary processes. It is noteworthy that the physical phenomena involved in the manufacturing process, which are decisive in terms of final properties of the parts, are linked to the manufacturing sequence and process parameters. The manufacturing trial was conduct to validate the part design and build up orientation. During the prototyping step, intermediate checks are conducted to evaluate the output of each process steps and a Non-Destructive Evaluation - NDE to ensure the part integrity according to the classification and requirements of the part. Once the part design and buildup orientation are approved in the prototyping step, the data files should be recorded and the results analyzed further for the part be produced in industrial scale.

A representative part of titanium around 100 mm in length, width and height as shown in Figure 4 was redesigned in accordance with the proposed DFAM method. This redesign comprises topology optimization and stress analysis by stiffness criterion, wherein the maximum von Mises stress level to be achieved is 600 MPa using mechanical properties of tensile strength prior obtained by tests. This stress level is equivalent to the conventional part design, Figure 4, to reach the same safety margin.

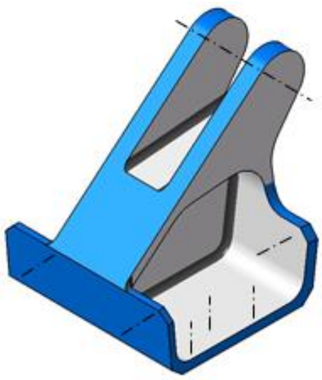


Figure 4. Design of titanium representative part for machining.

For the sake of verification, three redesigned parts were manufactured in accordance with the same raw material specification and processes parameters used to manufacture the test specimens.

3. RESULTS AND DISCUSSION

A structural airframe part under significant static loads but also liable to fatigue was selected to demonstrate the DFAM method as shown in Figure 4. The actuator support has the function of transmitting a rotational movement in the airfoil mechanism under a specific load, speed, frequency and service condition as temperature, humidity and pressure. Additionally, this part should meet requirements of safety, service life, maintenance, maximum weight and chemical compatibility with other nearby parts. The actuator support was largely designed to meet the stiffness criterion. This part should not strain excessively in operation to prevent the jamming of the mechanism. Then, the Ti-6Al-4V alloy was the raw material chosen to manufacture the actuator support due to better meet the requirements of that part.

As required for the design and manufacturing of the part, specimens were manufactured and tested to obtain the material properties Powder of titanium grade 5 ASTM Ti-6Al-4V with standard particle size of 20 - 60 μm was used. Laser power of 275 W, scanning speed of 975 mm/s and layer thickness of 50 μm are the L-PBF process parameters used as per Uhlmann *et al*. (2015) and buildup orientation as per VDI 3405/2 (2013). Complementary processes comprise surface finishing, heat treatment and inspection as per ASTM F2924 (2014). Subsequently, tensile tests were carried out in accordance with ASTM E8/E8M (2009) and fatigue tests as per ASTM E466 (2007).

It worth emphasizes that the specimens have been manufactured in three buildup orientations (0º, 45º and 90º) in relation to the build platform of the L-PBF machine as per VDI 3405/2 (2013).

The mechanical properties obtained by tensile tests and a comparison with literature values are shown in Table 2.

Table 2. Minimum Tensile Properties at room temperature, SI units.

X, Y, and Z Directions	Tensile Strength (MPa)	Yield Strength at 0.2 % Offset (MPa)	Elongation in 5 cm or 4D (%)
Mechanical tests	1006	941	19
ASTM F2924 (2014)*	895	825	10

*Literature value for comparison only

The results of the fatigue tests are shown in Figure 5 on a plot of maximum applied stress vs. number of cycles to failure/fracture.

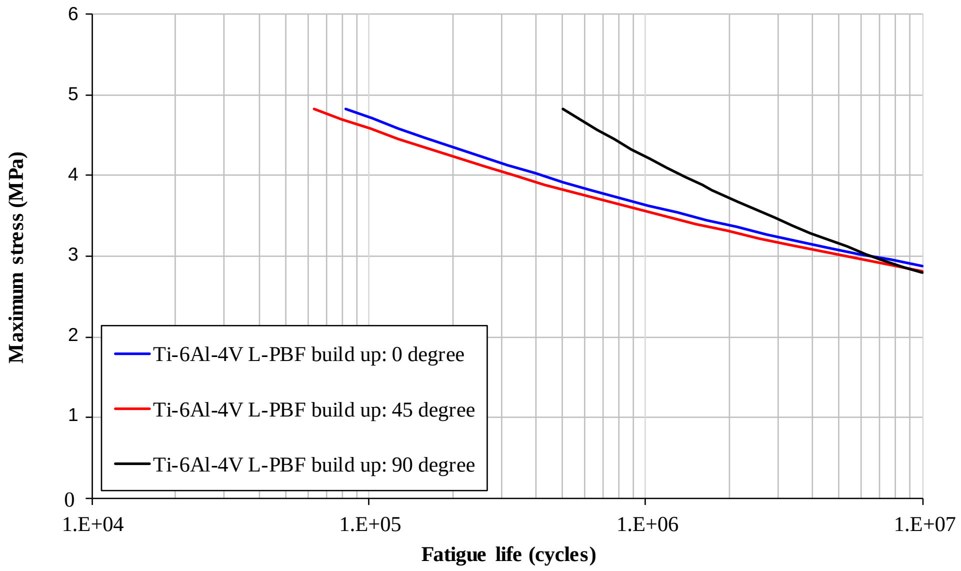


Figure 5. Ti-6Al-4V fatigue life, N (cycles), R = 0.1, Kt = 1.

The optimum strain energy was performed to meet the criteria of strength, stiffness and maximum raw material optimization according to the load case of the part in Figure 4. Thus, the topologically optimized geometry of the actuator support was sized in Hyperview software and shaped by its smoothing tool called OSSmooth as shown in Figure 6.

The design were interpreted in CAD system, following the topology optimization result as closely as possible but using design rules to meet the AM process capability and the finishing process characteristics.

The design for additive manufacturing were taken into account the part geometry optimization to maximize the benefits of the technology, such as saving of part weight, raw material, energy consumption and cost and, in addition, improve the part performance. Moreover, the design were performed under the integrated product development to obtain a compromise solution that best meets the product requirements but taking into account the manufacturing processes constraints.

The fourth step were to set the functional surfaces and perform the regular wall thicknesses of the optimized model having as reference the interface geometries of the nearby parts. As shown in Figure 7, the green planes represent those geometric constraints. Such geometrical elements have been set as fixed references (non-designable geometries).

The fifth step comprised taking the geometric center of normal cross sections extracted along the branches of the optimized model. Then, those geometric centers were connected by a 3D curve as the spines of the new model. Each spine matches the load path centerline that provided conditions to obtain the topologically optimized geometry.

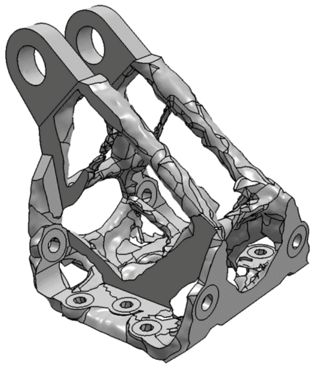


Figure 6. Topologically optimized geometry of the representative part.

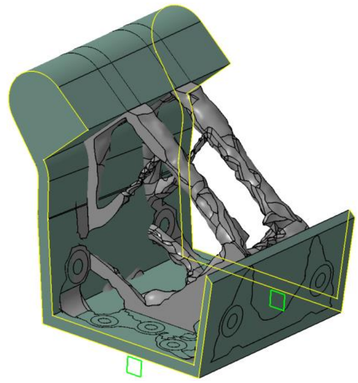


Figure 7. Regular walls of the support actuator according to fixed references.

The buildup orientation of the part is determined preliminary in the sixth step by an integrated product development approach taking into account the lower manufacturing time and the least amount of support structures. Figure 8 illustrates this design step, in which the gray color represents the topologically optimized geometry and the support structures are in red. The z-axis is normal to the buildup platform of the machine.

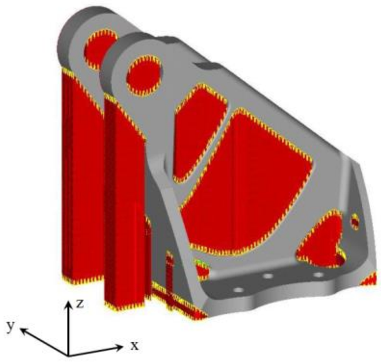


Figure 8. Preliminary buildup orientation of the part with support structures in red.

It is worth mentioning that the buildup orientation significantly drives the next design steps in terms of cross sections orientation of the part features and the 3D solid modeling. However, the buildup orientation must be validated in the prototyping step.

In the seventh step, regular geometric profiles were sketched on normal planes along the spine and concentric to this. Such profiles should superimpose the normal cross sections extracted along the branches of the optimized model and have an elliptical shape at the same buildup orientation of the part as shown in Figure 9 to save support structures, raw material and time consumed in manufacturing.

Thus, in the eighth step, the solid features were generated using the spines and their respective profiles following the topology optimization result as closely as possible. Figure 10 shows the result of the part solid step, wherein the green curve is a spine, yellow shapes are profiles and orange geometry is the solid feature performed by a CAD modeling tool.

In addition, pads, pockets, holes, chamfers and fillets were performed also following the topologically optimized geometry as closely as possible, but taking into account process capabilities of AM and post-processing to meet the part requirements. Figure 11 shows the representative part designed for direct metal part as result of the application of the proposed DFAM method. For comparison, the original design of the representative part is in Figure 4.

A parameterized 3D model is important to save time in the design reviews and structural verification as finite element analysis, whereas the smoothness and geometric uniformity are very important to inspect the part during its manufacture and service life.

On basis of the redesign result, a stress analysis validation were performed in the ninth step, wherein several static cases were analyzed. The maximum stress achieved 570MPa in the final design, which is far below the critical value for static load case. The maximum stress is 940MPa (yield stress of the processed material). Fatigue cases were also analyzed, with maximum stress of 150MPa, which is below the endurance limit. It can be concluded that the failure will never occur below 1,000,000 loading cycles.

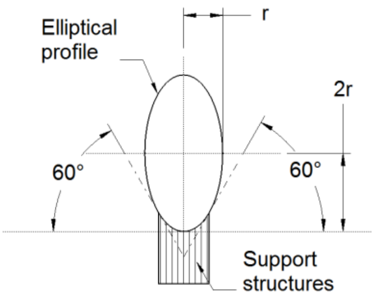


Figure 9. Elliptical shape profile, radius ratio 2 to 1

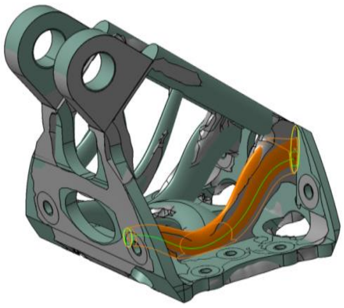


Figure 10. Complex feature detail superimposing a branch of the topologically optimized model.

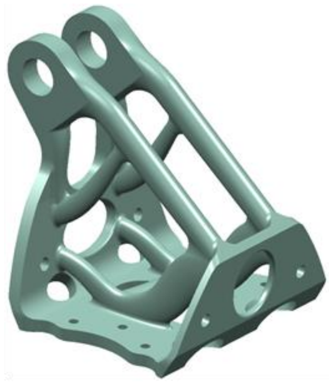


Figure 11. Design of titanium representative part as per the DFAM method for aerospace metal parts.

At first, validation confirms that the design is feasible. However, the main concern is the stress in the fatigue case for the real part. Thus, further fatigue tests should be performed to confirm whether this design would be actually acceptable.

In the tenth step, the tolerances of the part and its assembly were specified in the technical drawing to define the allowable deviations in form and possible size of individual features, and to define the allowable deviation between features. The result of the technical drawing drives the method of manufacture to meet the specification of the part. For airframe application, it is common that post-processing as finishing and drilling are required right after L-PBF process and heat treatment to meet the technical drawing specification.

In accordance with the eleventh step of the DFAM method proposed in this work the manufacturing trial was conducted leading to a verification of the part design. However, some pre-processing steps have to be taken before the manufacturing of the representative part by L-PBF, such as the buildup orientation of the part as per Figure 8, the construction of support structures, the slicing into layers and the setting of process parameters. As set for the test specimens, powder of titanium grade 5 ASTM Ti-6Al-4V with standard particle size of 20 - 60 μm were used as raw material and the L-PBF process parameters as per Uhlmann *et al*. (2015).

Although stable during the manufacturing of the part layer-by-layer, a delamination of support structures at the base of the part and part distortion was observed. Thus, it has been necessary to start again from the third step to set a new buildup orientation of the part and follow the subsequent steps according to the DFAM method for aerospace.

The support structures were strengthened to avoid delamination in next trial. However, the part had still critical deformation at plane surfaces after removal those supports.

The part were then positioned upside down on the substrate plate to strongly fix it and avoid thermally induced deformations in the trial. Thus, the parts were successfully manufactured by L-PBF without any support delamination and part distortion. Subsequently, the complementary processes of heat treatment, surface finishing and inspection have been successfully conducted as per ASTM F2924 (2014). The right-hand side of Figure 12 shows the representative part with support structures on the substrate and the left-hand side the finished part.

It is necessary to emphasize that developments of the L-PBF process simulation should be conducted to optimize the build-up orientation for minimum residual stress to reduce the numbers of trials to obtain distortion-free parts.

Table 3 shows a comparison in terms of raw material usage, part weight and buy to fly ratio between part designed for machining as per Figure 4, and part designed for additive manufacturing as per Figure 11.

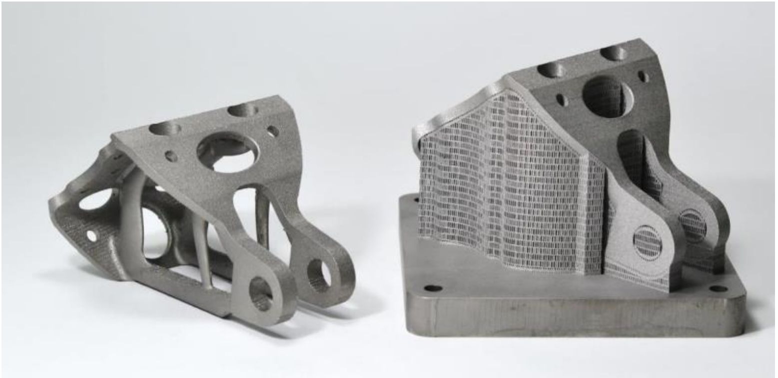


Figure 12. Representative part as L-PBF (left) and its support structure on the substrate plate (right).

Table 3. Raw material weight, part weight and corresponding buy to fly ratio for representative part according to the design and manufacturing process.

Design for	Raw material (kg)	Part weight (kg)	Buy to fly ratio
Milling	9.4	0.6	15.7:1
L-PBF	0.6	0.4	1.5:1
Savings	94%	32%	

It is noteworthy that by applying the DFAM method of direct metal parts, a substantial raw material savings and part weight reduction was achieved in addition to meeting the aerospace part requirements of smoothness and geometric uniformity.

In comparison with the method of integrated product and process development presented by Noorani (2006) in Figure 2, the proposed DFAM method presents in general similar macro steps of solid modeling, analysis, rapid prototyping and testing. However, this new method presents a detailed and concatenated block diagram encompassing firstly an analysis of the basic function of an airframe part and raw material selection according to the material properties datasheet. Second, the dimensional and geometric specifications in relation to the product requirements, material mechanical properties and the AM processes capability. Third, the verification of the part design and its performance in compliance with the product specifications and the AM processes capability. In addition, the DFAM method proposed in this work comprises 3D modeling strategy and integrated product development based on a topology optimization input taking in to account the capabilities of L-PBF, complementary processes and product requirements to provide design guidelines for direct metal parts. Whereas, the main drives are part integrity, lightweight parts and low raw material consuming achieving a smooth (continuity of curvature and tangency) and uniform (no abrupt dimensional variations) part geometry.

4. CONCLUSIONS

A literature review was carried out comprising advanced manufacturing concepts, metal additive manufacturing, principles of airframe design and design for additive manufacturing procedures wherein guidelines and design method were assessed. However, those general rules of DFAM are not sufficiently detailed and concatenated, nor do they present a proper sequence of tasks to meet effectively the aerospace design requirements.

The design method for direct metal part first proves to be innovative and effective to maximize the benefits of the L-PBF process in terms of weight reduction and raw material savings but also in conformity with the aerospace part requirements. In addition, the DFAM proved to be important to support an integrated product development by the functional and manufacturing optimizations. Those concepts were successfully used for designing of the demonstrator aerospace part of titanium.

Despite the preliminary positive result achieved, further design trials using other parts are necessary to fully validate the DFAM method detailed herein, as other combinations of functional requirements and geometrical constraints may pose additional challenges.

It should be noted that aerospace industry present an extra challenge for the direct metal parts made by additive manufacturing, including quality requirements (structural integrity), manufacturing process qualification and parts certification as well as geometric uniformity and lightweight parts.

As contribution, this work presents a DFAM method to help designers to develop products that are feasible to additive manufacturing, taking into account the aerospace parts particularities and technological capabilities. In addition, it was shown some important design checks and highlights gaps, progress, and needs to help identify opportunities for gains from the use of parts designed for the L-PBF process in the aerospace industry.

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