Design Right Once for Additive Manufacturing

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Abstract. Additive Manufacturing (AM) has been widely considered a key factor for innovative design. However, the utilization of AM has not been as high as expected, although the technology offers key innovative design capabilities, weight reduction, parts count and assembly consolidation as well as material saving. This low utilization is attributed to the lack of AM understanding, mature CAE/CAM software tools addressing AM specific issues such as design support structure generation and removal, residual stresses, surface quality. In most cases, Design for AM (DfAM) is a crucial requisite for a "Design Right Once" approach. Such an approach is shown in the current study using three parts as example: an arthropod's leg, a gearshift drum and an electric motor mounting frame. The implementation of geometrical conformal lattice structures and lattices with variable density are discussed. A structured design approach is presented and design dilemmas are solved in terms of a DfAM approach. Primary design optimizations are evaluated. Weight reduction is considered throughout the design and free form surfaces are being used. "Freedom to Design" principle is also portrayed and assembly parts consolidation occurs as a natural process of DfAM in comparison with previous design practices. It is concluded that, even from the primary design phase the design engineer can reveal his creativity because of the absence of constraints set by the traditional manufacturing technologies.

1 Introduction

Additive Manufacturing (AM) has been widely considered a key factor for innovative design. However, the utilization of AM technologies has not been as high as one could expect, even though the progress is substantial [1]. This could be partially attributed to a bottleneck in the Product Lifecycle (PL), from the initial conception to the first operational prototype. Even though AM is used extensively in the prototyping phase of product development [1], it is not considered as a manufacturing technology for mass production [1]. The design process is still held back by the designers' lack of understanding of AM capabilities [2]. AM technologies enabled the production of spectacular designs and this has contributed to the notion that AM demands very specialized and difficult design process. Software development has also contributed recently to the rise of AM use, especially in the last 5 years. Complex geometries like lattice structures, generative design, topology

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optimization have added a momentum to the Design for Additive Manufacturing concept (DfAM). Software developers have recently started to include AM capabilities in their CAD suites [3, 4]. Simulation of the AM process has also started to be included in some CAE/CAM suites [3, 5, 6]. However, these software tools are not being extensively used up to now. This contributed to the absence of design strategies and DfAM experienced designers. The necessity of DfAM is crucial for a “Design Right Once” approach [7]. Unnecessary trials can be eliminated by having design engineers mastering the capacities of AM [7].

In the current paper, three case studies are presented exploiting the powder bed fusion AM technology for plastic and metal materials. Two EOS printers are considered for manufacturing, an EOS Formiga P110 and an EOSINT M280 [8, 9]. All cases demonstrate the implementation of DfAM approach in the design of complex parts [10–15]. The first case is an arthropods’ leg, the second a gearshift drum (barrel) and the third a mounting frame. A structured design approach is portrayed and initial AM parameter selection such as orientation, platform position, layer height is shown. Certain design considerations are discussed and solved in term of DfAM approach and primary design optimizations, are evaluated. Lastly, the use of conformal lattice structures as an alternative to other topology optimizations is outlined. These lattice structures can be used for weight reduction or even aesthetically from the primary design phase. The “Freedom to Design” principle is also applied as is assembly part consolidation, exploiting thus the advantages of DfAM in comparison to previous design practices.

2 Design for Additive Manufacturing

The designer should be accustomed to the AM technology used for production [7]. This is a key factor for a successful design. The technology specific constraints and capabilities are the ones that will shape the final products. In the following, these constraints for powder bed fusion (PBF) [16] processes will be addressed for plastic and metal printing in order to follow effectively the DfAM approach [10, 11, 21–23, 12–15, 17–20]. Only after mastering DfAM, a successful “Design Right Once” approach may be achieved.

Orientation: The first parameter to consider is the orientation of the part inside the machines’ building envelope, since it is a limiting factor for the overall dimensions. They may also determine a specific orientation. Big parts will have less possibilities. The orientation has several effects on the final parts’ surface and overall strength. There are differences in the quality of the surfaces between the ones facing up and facing down. Free form surfaces tend to have better quality. Flat, facing sideways and downwards surfaces are usually worse than the ones facing up especially in SLM processes and due to the staircase effect in SLS. Also, the surfaces facing downwards to the platform, in the case of metal materials, need to have their support structures removed. Symmetrical parts are usually preferred by designers; but symmetry is not needed for AM. For instance, symmetry is something completely absent in topologically optimized parts. The so-called “banana effect” should also be considered. Long, SLS built parts tend to wrap along their longest dimension if oriented perpendicular to the re-coater blade. In metal printing (SLM) [16] the orientation of the part defines the areas where supports should be placed. If this is considered during the design phase, then the printing and the finishing of the part will be easier. Heat developed during printing must be dissipated from the part to the support structure and then to the metal base. Consequently, insufficient support structure leads to high thermal stresses and distortions of the final part. Support removal should be addressed early since it can minimize the post-processing. Finally, the smallest feature size depends on the orientation.

Platform position: Where the part is located inside the building volume influences the final properties. Powder bed processes exhibit part scaling in all directions by a shrinkage factor. It may make the dimensions of the final part inaccurate and therefore it must be considered. In SLS, the scaling factor of the z axis, depends on the positioning height. There are also slight differences in the accuracy between the center of the building platform and close to the boundaries.

Layer thickness: Both metal and plastic PBF processes have fixed, machine and material dependent, layer thicknesses. Parts are built up from slices. Therefore, their surfaces have a regular roughness structure known as “staircase effect”. They are like are stairs of riser equal to the layer thickness. In metal PBF printing this is of minor importance due to the small thickness of the layers (20 to 50 μm). In plastic processes (SLS) though, it ranges from 60 to 150 μm, tending to give very “jagged” surfaces. Therefore, the inclinations of flat surfaces should be altered during the design phase to avoid this. Since the layer thickness correlates to the exposure time per layer, it has an impact on fatigue endurance of the final part. Longer layer build times lead to less fatigue strength [24].

Material: The AM processes used currently in production lines utilize specific materials, mostly in powder form. Their cost is much higher than of conventional materials. Moreover, the price span between powders offered for AM is quite narrow. Therefore, the designer should take advantage of the better material quality and strength as well as of the design freedom offered by the AM in order to compensate for the higher raw material price. An advantage of AM is the possibility to print test specimens simultaneously with the part. In this way, tensile strength tests, surface hardness measurements etc. can be performed to increase the quality assurance.

Generative design, topology optimization: The extensive use of FEM and the evolution of optimization algorithms initiated a new design approach. Mass and volume are considered as cost and by solving a minimization problem optimized parts can be obtained[25]. The resulting geometries are quite organic-like and rather complex. Their production is almost impossible without AM technologies. Recently, artificial intelligence (AI) has been introduced and thousands of geometric models can be produced and evaluated quickly. The resulting truss-like structures need inner support in order to be printed. They could pose a serious problem in removing the part from the platform and poor surface quality on the interconnecting struts. Topology optimization and generative design algorithms both restrict the role of the design engineer. Special care should be taken to the final appearance of the products, since some parts could lose or gain marketing value by incorporating such shapes.

Assemblies: A potential advantage of AM is assembly part number consolidation. Since there are less geometry restrictions, parts that were split in order to be manufactured can now be unified or even designed as one part from the start. Certain types of linkages and mechanisms can be printed as one part and even new types of linkages can be used to further reduce the assembly’s part number. Large assemblies can now be printed in one batch as a single piece, providing a very cost-effective feature.

3 Design Right Once

The proposed strategy is demonstrated by applying it to three case studies. A leg of a six-legged arthropod, a gear shift barrel and a motor mounting frame. The first part is made from polyamide PA12 and was printed in an EOS Formiga P110, while the second is printed in MS1 steel in an EOSINT M280.

The design strategy for a "Design Right Once" approach, is as follows:

- An initial rough shape, that satisfies the part's functionality, is designed. It is parametrically described so that easy modifications can be applied between iterations.
- The shape is divided into two spaces: Interface and Design space.
- Any parts adhering to the interface space of the part can be consolidated to decrease overall part count. The process restarts with the new geometry.
- According to the importance and surface tolerances needed, the parts build orientation is chosen to provide good quality of important surfaces (SLS/SLM) and minimize supports (SLM). Also, the platform position can be determined.
- Choice of optimizations that can be applied to the design space, such as topology optimization, generative design, lattice structures etc., having the underlying support structure in mind. Depending on the chosen optimization method the support structure may be further optimized.
- Build layer thickness is chosen to reduce building time, accommodate support structure peculiarities and small features like lattice cell size. Also, the part parameters can be re-evaluated according to the building parameters.
- Interface space optimization can also be considered at this point, like inner space lattice structures with or without outer skin.

3.1 Test case 1

The evolution of the design of a leg of a six-legged arthropod is shown in Fig. 1. The interface and design spaces are defined on the first design iteration. Between iterations, they may be changed but in this case they remain the same.

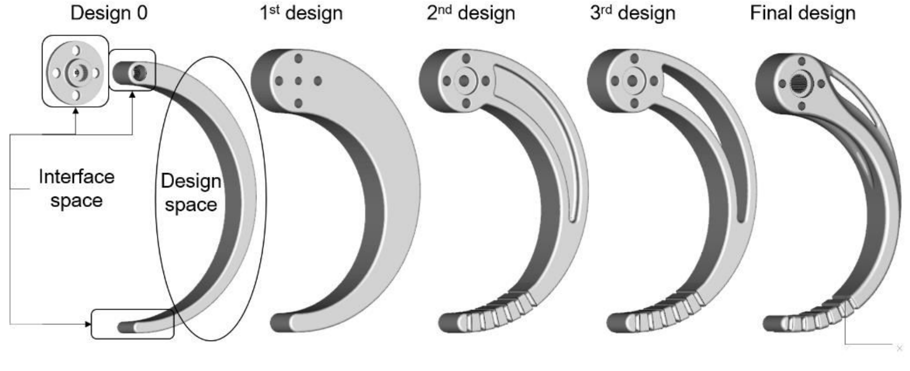
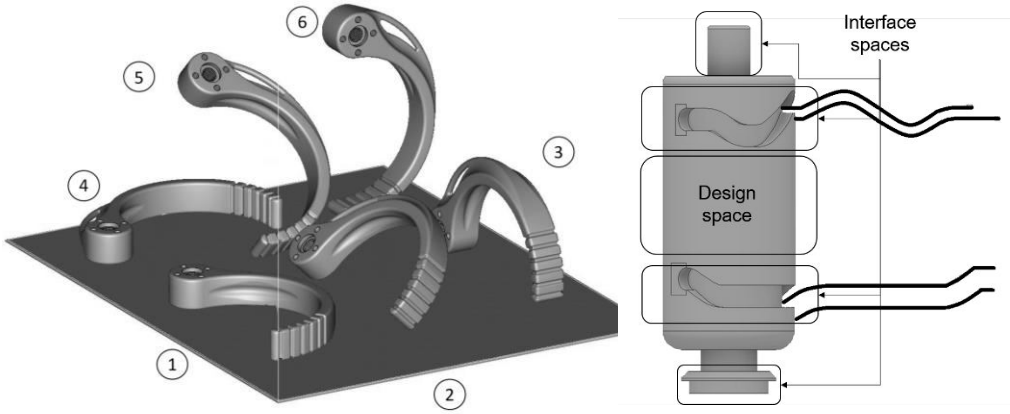


Fig. 1. Design history of test case 1

The purpose of the leg is to support the robot. It has to be elastic enough to let it bounce, as a kind of a suspension system. Therefore, it must be flexible enough and strong at the same time. EOS PA2200 was the build material. After the design was finalized, several orientations were considered (Fig. 2a). Due to the dynamic bending of the leg, smooth surfaces and fillets were beneficial and therefore orientation 1 was chosen.

The initial two parts leg assembly was reduced to just one part. and FEM was used to find the proper leg thickness. The FEM results showed that the grooves starting at the tip where safe and O-rings elastic bands were used to provide extra grip. The legs were printed in an EOS Formiga P110 (SLS), with a layer height of 100 μm. The part files were kept in a parametric form, so many details like fillets where altered to compensate for the layer height.

Lattice structures or topology optimizations were not carried out on the semi-circle part of the leg. On the back rib it is possible to use meta-materials, for variable stiffness.

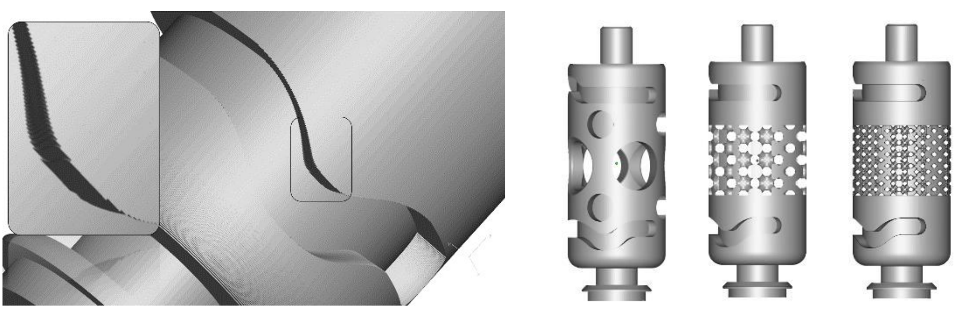


(a) (b)

Fig. 2. a) Possible orientation inside the Formiga P110 building envelope, b) Test case 2, a gear shift barrel of a Honda 600 RR motorcycle motor.

3.2 Test case 2

The second test case is a gear shift barrel (drum) of a Honda 600 RR motorcycle. This part was redesigned for the Aristotle Racing Team formula student race car. The initial design is shown in Fig. 2b, along with the interface and design spaces. It has two custom designed guiding rails. The tight tolerances and the smooth surface needed in the guiding groove leading us to select a building layer thickness of just 20 μm (Fig. 3a). The next AM parameter is the

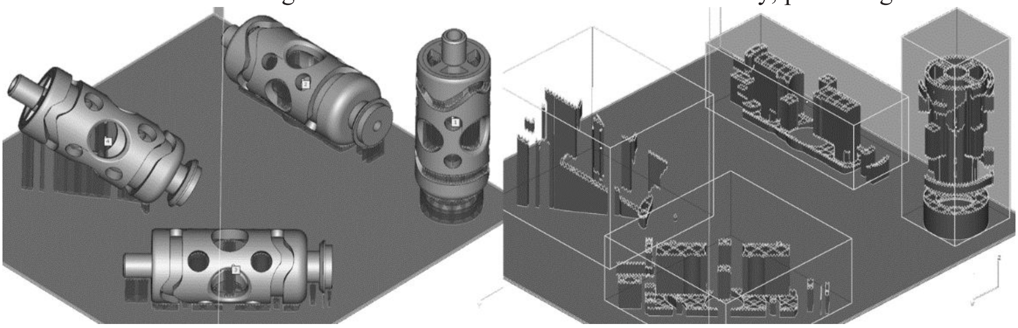


(a) (b)

Fig. 3. Test case 2. a) Part detail view of groove and close up, b) barrel without holes, lattice with 10 mm and 5 mm cell size

part orientation. The optimal was found 45^{o}, as shown in Fig. 4. With this orientation, the support structure needed is adequate for supporting the part during building and for heat dissipation. The material selected is the EOS MS1 [26] i.e. tool grade steel. The inertia of the barrel needs to be reduced. In this way, an electric actuator instead of a pneumatic one can be used, leading to considerable weight saving. The part is hollowed out to reduce the mass. To further reduce the weight, lattice structures were designed in the middle section of the barrel. From several available cell-types the so-called "body diagonals with rounded nodes" with a structure unit cell size of 5 mm was selected. The structures were generated by cutting the part into subparts and then applying the lattice generator to the designated spaces. This procedure gives a better workflow, since FEA may be performed to the subparts. Thus, by separating the parts into subspaces, a more modular design workflow is developed, where the lattice structures can be analyzed separately until the optimizations are complete.

As it can be seen in Fig. 3b the lattice cells are not oriented radially, producing areas of



uneven material distribution. Therefore, a conformal lattice structure is considered. The

Fig. 4. Test case 2, building platform orientation test and corresponding support structures

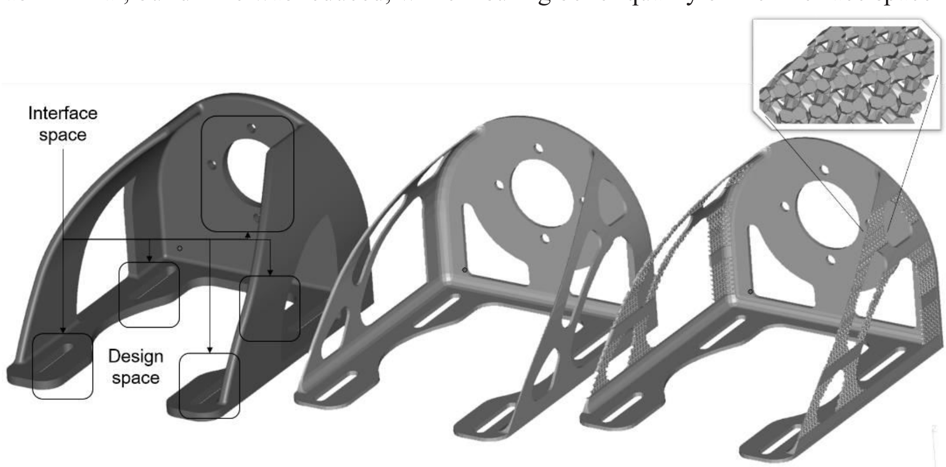
entire structure can be adjusted either according to loading of the part or according to the part geometric boundaries [27].

Adjusting to loading follows the same methodologies as the topology optimization algorithms do, while considering the boundaries results in lattice structures similar to those found in nature [28], as for example in the inner of bones, in butterfly wings etc.

3.3 Test case 3

The third test case, an electric motor mounting frame, started as the leftmost design of Fig. 5, where the interface and design spaces are defined.

Moderate topology optimization was applied to the initial design and the middle part of Fig. 5 was obtained. For the orientation, the 45^{o} inclination angle was used, as in test case 2, but with the base kept flat to the printers build platform. This way the support structure was minimal, build time was reduced, while insuring better quality of the interface space



(a) (b) (c)

Fig. 5. An electric motor mounting frame (from left to right), a) initial part, b) topology optimized, c) lattice structures on topology optimized struts.

surfaces. This choice lead to the use of a layer thickness of 20 μm, in order to use the "MS1 Surface" machine parameters.

The combination of lattice structures and topology optimization either on different part spaces (Fig. 5b) [23] or by applying lattice structures on topology optimized struts (Fig 5c) [29], are very promising. A 28% reduction in weight was achieved by simply applying lattice structures to specific areas. The cell unit size was chosen 2.5 mm, the same as the initial struts thickness. Current SLM technologies can achieve struts of the unit cell less than one millimetre [30, 31], so the chosen value can be successfully printed.

4 Concluding remarks

Additive Manufacturing technology has a strong impact on almost all aspects of design. On one hand barriers imposed by the traditional design methods are removed, but on the other hand new restrictions are imposed. Designers have to consider orientation inside the building volume, layer thickness, support structure and so on. Moreover, they must become familiar with the multitude of various AM processes and the distinct and characteristic part properties they provide. Materials with upgraded properties or even new materials are becoming available for AM. Traditional CAD, CAM and CAE software suites are being enriched with AM modules. Concurrently, new software tools are being developed aiming to support the designer in exploiting the new AM possibilities and help him to incorporate new features in the final products. Optimization algorithms are gaining importance since new design features are becoming possible. Besides topology optimization, lattice structures are an exciting new possibility. They provide excellent structural properties and new functionality like meta-materials. Specifically, in metal printing processes, they provide solutions to support lightweight structures and material saving. Various pattern strategies in the lattice structure, such as density according to parts' loading, conformal mapping, different cell types, will provide robust and lightweight parts. Finally, AM technologies are being used in Industry 4.0 (Industrial Internet of Things, IIoT), due to the digital versatility that is inherent in the processes and will be the workhorse of this evolution.

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