Laser Additive Manufacturing and Bionics: Redefining Lightweight Design

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Abstract

New layer wise manufacturing technologies such as Laser Additive Manufacturing (LAM) allow innovative approaches to product design. Especially for lightweight design in aircraft applications LAM offers new possibilities for load-adapted structures. However, to fully capture lightweight potential of LAM technologies new design guidelines and processes have to be developed. A novel approach to extreme lightweight design is realized by incorporating structural optimization tools, bionic structures and LAM guidelines into one design process. By consequently following this design process designers can achieve lightweight savings in designing new aircraft structures.

Keywords: Additive Layer Manufacturing; Laser Additive Manufacturing; Selective Laser Melting; light weight design; bionic design; structural optimization

1. Motivation

In addition to already existing American competitors, a rising number of internationally acting companies from Far East and Russia lead to a steadily increasing pressure of cost efficiency and innovation in the European aircraft industry. The increasing struggle for efficient aircrafts can be noticed, among others, in the rising use of lightweight structures based on structural optimization tools. The introduction of these load optimized components results in falling lot sizes, highly complex parts and the demand for reduced production times at lower raw material charges. Thus, manufacturing by conventional processes becomes increasingly cost-intensive. Therefore, a flexible and fast manufacturing process that is able to produce manifold product variants of a high geometric complexity is necessary. A possible process to cope with these challenges is Laser Additive Manufacturing (LAM) [1].
The individual production steps of the LAM process are shown in Figure 1. In the preprocessing a 3D-CAD-model is divided into horizontal slices with thickness corresponding to the layers in the production process. Typical layer thicknesses for TiAl6V4 are hereby 30 μm – 50 μm. Subsequently to the “slicing” the prepared data is transmitted to the SLM machine in which the actual manufacturing process occurs in three repeating steps. First a powder layer is applied to the base plate and in the second step exposed by the laser beam. Due to the energy input of the focused laser beam the powder melts and solidifies into welding beads after exposure. In every single layer the beam melts the surface area corresponding to the CAD – model slice. With each new layer the base plate is lowered and powder is applied. After completion of all layers the part can be taken from the powder bed and unmelted powder recycled for further production.

![Figure 1: Process of Laser Additive Manufacturing](image)

The stepwise production causes the reduction of complex three dimensional geometries into simple two dimensional manufacturing steps and enables the production of highly complex parts. Thus, nearly any structure can be manufactured which facilitates the realization of designs in accordance with the parts stress distributions under load. It therefore permits new design approaches for lightweight structures that were not possible up to now due to the conventional manufacturing processes inherent restrictions. However, the knowledge of its capabilities, especially its design-freedom, is currently still limited to experts [3,4].

### 2. Innovative Design Process for Bionic Lightweight Constructions

Pushing the limit of lightweight design has always been the driving force of aircraft design. In order to facilitate this, an increased usage of structural optimization tools can be seen. The structural optimizations goal, especially the topology optimizations one, is to numerically determine the parts volume which is of structural relevance out of a given design space [6, 7]. Because of their geometric complexity, up to now the results of these calculations were hardly convertible into manufacturable parts due to the conventional manufacturings inherent design restrictions. Compared to conventional tooling, the risen grade of design freedom of LAM facilitates a more radical implementation of FEM-based structural optimization into the design process and allows completely new approaches for designing functional parts. It is therefore possible and even necessary to directly implement bionics into the design process. Figure 2 shows the design process for bionic lightweight constructions that combines structural optimization and bionics in order to fully exploit the ALM’s design freedom [5].
list of requirements
- manufacturing constraints
- interfaces
- material
- loading
- acceptable strains
- acceptable distortion
- acceptable buckling factor
- acceptable eigenfrequencies

topology optimization
- design space modeling
- FEM-modeling
- loading
- geometrical constraints
- design variables
- objective function
- solver calculations
- resulting geometry

interpretation of results
- lightweight design guidelines
- manufacturing restrictions
- bionic searchfield analysis
- torsional load
- shear load
- bending load
- tensile / pressure load

remodeling in 3D-CAD

FE-analysis
- inspection of conformance regarding the requirements

requirements fulfilled

final design

requirements partially not fulfilled

requirements not fulfilled

Figure 2: design process for bionic lightweight constructions
The processes basis is the definition of a list of requirements combining all necessary data for the part design, which collectively have to be met to fulfill the parts functionality. The requirements also represent the objectives needed for the definition of the structural optimization process. The software calculates in consideration to these objectives the optimal material allocation according to the parts installation situation. Due to the solutions lack of manufacturability of the optimization result, see figure 3, and the possibility of non-unique solutions from the optimization algorithm, the result has to be understood as a design suggestion.

In the following design step an interpretation by the designer takes place in order to convert the optimization result into a lightweight design. Alongside the use of conventional light weight design guidelines it is essential, due to the currently only marginal acquaintance of the processes inherent restrictions, to incorporate LAM related design guidelines into the design process. By this means the manufacturability and profitability of the designed parts can be assured. Especially the processes distinctive restrictions, like the necessity for support structures, the anisotropic nature of part strength and thermal induced stresses, respectively their prevention, have to be considered due to their fundamental differences to conventional manufacturing restrictions. By defining this sub step the designer is obligated to consider LAM specific restrictions and therefore the viability of the component at the highest possible economic efficiency is enforced. Based on the results of the interpretation the remodeling of an appropriate geometry using 3D CAD is conducted. In order to verify the fulfillment of the parts requirements the generated 3D-CAD model subsequently has to undergo a structural analysis. If the chosen design does not meet the required demands an iterative redesign process takes place.

The elucidated design process illustrates the significant influence the designer has during the interpretation of the optimization results and thus the end-designs final weight. To guide especially inexperienced designers and taking advantage of the increased design freedom LAM offers for even more radical lightweight designs, the direct implementation of bionics is introduced in this step [8]. In simple terms bionics or biomimicry means “learning from nature” [9]. The undeniable benefit of this relatively new field of research is the exploitation of solutions that have been optimized due to the process of natural selection for generations. However, the application of natural structures by the designer premises a tremendous expert knowledge concerning the possibilities and diversity of such structures. For this reason supporting inexperienced designers in choosing adequate structural elements is inevitable.

In order to facilitate a plain application of the collected bionic analogies, a bionic search field analysis was defined and arranged in basic loads according to the applications mechanical nature. Applying the bionic search field analysis requires an accurate analysis of the structural optimizations results. The goal is to segment the latter in structural components according to basic loads which allows a facile assignment of natural solutions deposited in the search field database. The database exploits additional light weight potential and supports the designer in the search for adequate structures, see figure 4.
Further the processes application can help the designer to leave deadlocked paradigms and exploit new possibilities for lightweight design. The consequent use of the developed design process shows a tremendous weight saving potential for optimized bionic structures. In several analyses weight improvements of up to 80% could be shown [5, 8]. Despite showing the apparent theoretical potentials and adequate applications of this new production technology to a wide spread audience the proof of its economic application is paramount to its insertion into the competitive market of industrial manufacturing [10].

3. Economic Analysis of LAM and Discussion

Due to the necessity of using Laser Additive Manufacturing to produce such highly complex lightweight structures the weight saving is accompanied with additional manufacturing costs. However, the cost effectiveness for LAM lightweight designs for aircraft applications could be proven in an extensive Business Case conducted on this topic. Additional costs of only 129€ per saved kilogram with this new design approach is accompanied by potential investments of 1.000€ per saved kilogram and saved operational expenses of up to 20.000€ over the aircraft lifecycle. Therefore, the optimized bionic lightweight structures can contribute to the ongoing search for weight improvements of the next aircraft generations [5].

Summarized, this survey presents an innovative design process whose application can lead to significant weight reductions. Limited by the current 3D-CAD-Tools and the not yet holistic design guidelines for LAM the results of the conducted design optimizations only show the beginning of what can become an essential new way of designing lightweight constructions.

References

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