Topography optimization and laser additive manufacturing in design process of efficiency lightweight aerospace parts

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Abstract. The paper presents the application of topology optimization and laser additive manufacturing in the design of lightweight aerospace parts. At the beginning a brief overview of the topology optimization algorithm SIMP is given, one of the most commonly used algorithm in FEA software. After that, methodology of parts design with using topology optimization is discussed as well as issues related to designing for additive manufacturing. In conclusion, the practical application of the proposed methodologies is presented using the example of one complex assembly unit. As a result of the new design approach, the mass of product was reduced five times, and twenty parts were replaced by one.

1. Introduction

In the modern high-tech industries, creating best-in-class product is a key to success. On the one hand, the product must perform the main task, and, on the other hand, it should be cost-effective. In the aerospace industry, one of the important criteria of efficiency is the weight of the product, the reduction of which reduces fuel consumption, pollutant emissions and increases the carrying capacity. Two trends to achieve this goal are topology optimization and additive manufacturing technology. Topology optimization allows designing lightweight and strong enough parts and additive technology allows manufacturing parts almost any complexity very fast. It should be noted that these innovations require a completely change of approaches to the design of parts.

This paper presents a brief overview of the latest advances in topology optimization and special design techniques for additive manufacturing in aerospace industry, describes the design process of efficiency of lightweight parts.

2. Topology optimization

Topology optimization (TO) is a structural optimization method that calculates the optimal material distribution in a design domain for a given problem. There are a lot of TO algorithms, as well as specialized software. The Solid Isotropic Material with Penalization (SIMP) algorithm is one of the most commonly used algorithm in practice. Algorithm SIMP is fully described in a book [1] and in articles [2, 3]. The SIMP algorithm is based on the finite element (FE) method, where special pseudo-density parameter \( x_e \) is used to solve the optimization problem, which determines Young’s modulus \( E_e \) as follows:

\[
E_e(x_e) = E_{\text{min}} + x_e^p (E_0 - E_{\text{min}}), \quad x_e \in [0, 1]
\]
where $E_0$ is Young’s modulus of material, $E_{min}$ is Young’s modulus of material in a void region, $p$ is a penalization factor.

The mathematical formulation of SIMP TO algorithms is presented below:

$$
\min_x \quad c(x) = U^T K U = \sum_{e=1}^{N} E_e(x_e) u_e^T k_0 u_e
$$

subject to:

$$
\begin{align*}
V(x)/V_0 &= f \\
K U &= F \\
0 &\leq x_e \leq 1
\end{align*}
$$

where $c$ is the compliance, $U$ and $F$ are the global displacement and force vectors, $K$ is the global stiffness matrix; $u_e$ is the FE displacement vector; $k_0$ is the FE stiffness matrix; $N$ is the quantity of FE; $V(x)$ and $V_0$ are final and initial volume; $f$ is the prescribed volume fraction.

To analyze the effect of various TO parameters on the result such as volume fraction $f$, the filter radius and quantity of nodes, a comparison on a simple example was made. As it is seen from Figure 1, with the variation of these parameters, the results are significantly different.

**Figure 1.** Topology optimization of a 2D design domain: a – boundary conditions; b – results with different volume fraction; c – results with different filter radius; d – results with different quantity of nodes.

The best manufacturability results can be obtained with a changing filter radius, a quantity of nodes, and the strength and stiffness of the structure can be increased with a changing volume of fraction. The definition of these parameters is a matter of compromise between computational costs and the quality of the TO solution. To effectively solve the practical optimization problem, it is necessary to create economical and at the same time reliable FE models and to set the dimensions of the element two or three times smaller than the size of the minimum manufactured component (for example, thickness of ribs and shells, fillet radius and etc.).

With the development of additive manufacturing technologies, a large number of research works related to the application of TO to the design of aerospace parts have appeared. In article [4], the review of software for TO was carried out. In articles [5, 6, 7, 8], TO of aerospace parts and methodologies for design was presented. Analyze these works and optimize a different aerospace parts, own methodology of designing lightweight parts were developed. The main stages of this methodology are shown in Figure 2. Next, important points of each of the stages will be considered.

At the stage of data preparation, the definition and sorting of load cases are very important for obtaining strong and reliable parts, the definition of technological and technical constraints for parts is no less important. All these data will be specified as different parameters and settings in TO software.

At the topology optimization stage, creating of the design space is very important, after that an iterative TO process begins, which consists of directly from TO, technological and FEA testing of result and, if necessary, changing TO parameters.

At the topology optimization result adaptation stage, fast and qualitative creating of the optimal CAD geometry is very important. The following methods can be used: creating parametrized 3D
geometry in CAD or non-parametrized bionic geometry using splines in special hybrid modeling software, and STL editing for rapid analysis of result and prototyping. In conclusion, at the stage of FE analysis, an important decision is required to complete or modify the design process. This methodology is well proven in the design of aerospace parts. The part presented in Figure 2 was three times lighter than original component and strong enough.

**Figure 2.** Design process of lightweight parts with topology optimization.

3. **Design for laser additive manufacturing**

Additive manufacturing (AM) opens up a lot of opportunities previously unavailable to traditional manufacturing technologies. From the point of design, it became possible to use the following elements:

- Bionic topology of part;
- Internal channels for cooling;
- Integration of parts and functions for efficiency in weight, cost and assembly;
- Lattice microstructure for lightweight and use in medicine application.

At the same time, due to the complexity of the AM technological process, the use of AM is not always cost-effective. To increase the cost-effective of design and production, it is necessary to use special techniques of design for AM and optimize an AM technology process. The main stages of AM design and production are presented in Figure 3.

At the design stage, the initial part or assembly must be redesign taking into account the advantages of AM and the capabilities of the SLM machine. In the case of success, redesign part will have unique characteristics. In articles [9, 10] examples of the application of special design methods for AM are presented. At the stage of pre and post SLM production, economic efficiency can be achieved by selecting the right orientation of the parts in the chamber, which will affect the volume of supporting
structures and the laboriousness of further processing (cutting off parts from the plate, removing support structures and etc.). Stages that should be given a special attention for saving resources in planning AM production are marked in green in Figure 3. An example of design for AM is shown in Figure 4.

**Figure 3.** Stages of design and production in AM.

![Diagram](image)

**Figure 4.** Example of design for AM: a – initial assembly; b – optimization process; c – final part, result of integrating parts and functions.
4. Result and discussion
Using the TO and design techniques for AM, a new part was obtained, which is shown in Figure 4. To maximize the benefits of AM technologies, the following steps were taken in the design process:

- Improving the shape of internal channels;
- Reducing the mass of parts and improving their mechanical characteristic by means of topology optimization;
- Integration of basic parts and fasteners.

Thanks to the proposed methodologies presented in Figures 2 and 3, the mass of the part was five times lighter than the original assembly, and twenty parts were replaced by one. Also, the systematization will allow one to design better AM parts with less AM production cost.

5. Conclusion
TO and AM are two trends that allows creating unique best-in-class products, but it is quite a difficult task, for the solution of which it is necessary to take into account design goals, product price and time to market.

The development and implementation of the proposed methods will have a positive impact on AM design and production.

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References

[1] Bendsøe M P, Sigmund O 2003 *Topology Optimization: Theory, Methods and Applications* (Springer)
[2] Sigmund O 2001 A 99 line topology optimization code written in Matlab *Struct Multidisc Optim* 21 120–127
[3] Andreassen E, Clausen A, Schevenels M, Lazarov B S, Sigmund 2011 O Efficient topology optimization in MATLAB using 88 lines of code *Struct Multidisc Optim* 43 1-16
[4] Reddy K, Ferguson I, Frecker M, Simpson T W, Dickman C J 2016 *Proc. ASME 50107* vol 2A
[5] Sebra M, Azevebo J, Araujo A, Reis L, Pinto E, Alves N, Santos R, Mortaguaj P 2016 *Proc. Structural Integrity* 1 289–296
[6] Emmelmann C, Sander P, Kranz K, Wycick E 2011 *Physics Procedia* 12 364–368
[7] Faskhutdinov R N, Dubrovskaya A S, Dongauzer K A, Maksimov P V, Trufanov N A 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* 177 012077
[8] Dubrovskaya A, Dongauzer K, Faskhutdinov R 2017 *MATEC Web of Conf.* 129 01067
[9] Orquera M, Campocasso S, Millet D 2017 *Proc. CIRP* 60 223 – 228
[10] Kamps T, Gralow M, Schlick G, Reinhart G 2017 *Procedia CIRP* 65 259 – 266