A novel approaches to components design additive manufacturing process

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Abstract. In accordance with the concept of additive technologies which is layer by layer synthesis of products, there is a need for a new approach to components design. One of the main tools to be operated is numerical modelling which can provide the designer with an integrated approach to the development of new products if applied skillfully. The numerical modelling, besides carrying out strength calculations, includes topological optimization and creation of cellular structures with the help of which it becomes possible to create light-weight products with preservation of required strength characteristics. In this paper both methods were applied based on the example of a mounting bracket: topological optimization and creation of cellular structures. The paper presents the results of calculating the stress-strain behaviour of the source and target structures, allowing to estimate the possible reduction in product weight and quantity of the consumable material when using an additive technology.

1. Introduction

Additive manufacturing is the process of producing components when these components are produced by adding material layer by layer. This technology allows manufacturing a finished product with a very complex geometry which is difficult or impossible to be manufactured by traditional methods [1]. Additive manufacturing includes such technologies as selective laser sintering (SLS), direct metal deposition (DMD), electron beam melting (EBM), selective laser melting (SLM). One of the most intensively developing technologies of additive manufacturing is selective laser melting of metal powder materials, which is widely implemented in process chain [1].

Based on the concept of additive technologies, it is necessary to use various means of geometry optimization and/or optimization of the internal space of the model. Optimization of the source model can achieve the significant reduction of the component weight (including the reduction of raw material consumption to produce it) while maintaining the required strength characteristics of the component, and also maintaining (and sometimes improving) the technologically optimized model compared to the original one. The first of the considered methods is topological optimization. Topological optimization (TO) is a method of structural optimization which uses numerical modelling and calculates the optimal material distribution within the source volume of a 3D model for a specific task [2]. The resulting 3D model becomes the so-called "bionic design". The second method is the creation of cellular structures. As part of this work, the main objective is to evaluate the effectiveness of the component weight...
reduction and, consequently, the decrease in the amount of the material used in its additive manufacturing by running TO and creating cellular structures on the example of a mounting bracket. The calculations of the stress-strain behaviour of each obtained variant will be carried out and the obtained results will be compared.

2. Materials and methods
Models were developed in the Inspire software package by the solidThinking company according to the two methods of a new design approach. This software package allows creating different design models using a wide set of tools, performing static calculations of stress-strain behaviour, carrying out numerical modelling of the topological optimization taking into account the method of subsequent component manufacturing. The redesign of the mounting bracket components and subsequent numerical modelling were carried out in accordance with the methodology presented in Fig. 1.

![Figure 1. The methodology of redesigning the existing components for additive manufacturing](image)

In this work, numerical modelling applied the mechanical characteristics of titanium alloy Ti6Al4V (Table 1) obtained through selective laser melting [3].

| Specimen tested in | Young's Modulus, GPa | Yield Strength, MPa | Ultimate Strength, MPa | Deformation, % |
|--------------------|----------------------|---------------------|------------------------|---------------|
| Tensile             | 42 ± 2               | 1056 ± 29           | 1351 ± 34              | 5.5 ± 0.8     |

Table 1. Mechanical characteristics

As a source 3D model shown in Figure 2, we took a mounting bracket as the most suitable component type for TO.
3. The results of numerical modelling of TO and cellular structures and their discussion

To assess the effectiveness of reducing the component weight, the initial step was to perform inverse modelling, namely to increase the volume of the 3D model retaining the basic component geometry.

Topological optimization is a mathematical approach that solves the task of optimal material distribution in a limited space with given loads and limiting conditions so that the solution satisfies the required conditions. The design analysis is performed through the finite-element method, while the optimization itself can be run due to one of the known optimization methods [5].

Solving the task of finding the optimal material distribution using a numerical method, a standard approach is to discretize the task through finite elements. In optimization tasks, there are two interesting parameters which include displacement $u$ and stiffness $E_i$. When using finite elements for these two parameters and assuming constant stiffness for all elements, we get the following [6]:

$$\begin{align*}
\min_{u,E_i} f^T u \\
\text{s.t.} \quad K(E_i)u = f \\
E_i \in E_{ad}
\end{align*}$$

where $u$ and $f$ are vectors of displacement and force, $K$ - the stiffness matrix, $E_i$ - the stiffness of the $i$ element, $E_{ad}$ - allowable stiffness tensor for our design.

The result of the optimization process is a 3D model (Fig. 3, Fig. 4) with the material distributed to meet the set boundary conditions.
To verify the efficiency of the final 3D model of the mounting bracket component we calculated the stress-strain behaviour for all three models, Figures 2-4. The calculations were performed through the finite element method. To make the calculations, as well as to carry out topology optimization, we set the boundary conditions and the parameters for partitioning a finite element grid. Figure 5 and Table 2 present the results of calculating the stress-strain behaviour of three model variants.

![Figure 5](image_url)

**Figure 5.** The results of calculating the stress-strain behaviour of three model variants: a – the source model, b – the model after topological optimization, c - the model after the creation of a lightweight cellular structure; 1 – stress according to von Mises, 2 – displacement, 3 - strain

| The load of 5000 N in the vertical direction | Stress, MPa | Displacement, mm | Strain, 10^-3 | Volume/mass, cm³/g |
|--------------------------------------------|-------------|-----------------|---------------|---------------------|
| A source model                             | 486.1       | 3.16            | 2.507         | 877.84 / 3887.78    |
| The model after topological optimization    | 213.1       | 1.711           | 1.508         | 746.85 / 3307.63    |
| The model with a cellular structure         | 482.1       | 4.938           | ∅ rods of 0.5-1.6 mm | 364.3 / 1613.85     |

**Table 2.** Comparison of the results of calculating the stress-strain behaviour

4. Conclusion

Comparison of the data showed that the topologically optimized component with the same load had internal stresses two times less than the source component, and the optimized volume reduced by 15%.

Further optimization led to the fact that the same load in the source model and the cellular-structured model causes comparable internal stresses but increased displacement. However, comparing the volume of the powder used, we conclude that the volume of the cellular-structured model reduced by 58.5%.

Thus, the considered example shows that the efficiency of optimization to reduce the amount (weight) of the components for additive manufacturing is sufficient (can reach up to 50% and more) for its application in designing components.
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