Topological optimization of a part taking into account technological constraints

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Annotation. In this work, the topological optimization of an aluminum alloy bracket with specified mass restrictions and maximum von Mises stress intensities arising under the influence of load is carried out. The part was redesigned for the additive manufacturing method without forming a support structure, for this, restrictions on the overhang angle between the surfaces of the part and the build platform were used, all surfaces are considered self-supporting. Comparison of strength and stiffness characteristics of parts for bracket options, including both the original one, created by the designer, and those obtained after optimization, taking into account and without taking into account restrictions on the method of technological manufacture of the product, is performed.

1. Introduction
In this paper, the topological optimization of the bracket used in the aircraft engine industry is carried out. The topological optimization algorithm is based on the SIMP (Solid Isotropic Material with Penalization) method. The main idea of the method is the introduction of an additional characteristic - the field of the virtual density of the material of the part being optimized, the physical and mechanical properties of the material at a point or some area are taken to be dependent on the virtual density. The SIMP algorithm is implemented in conjunction with the finite element method. With a predetermined final mass of the product, the result of the algorithm operation is the optimal distribution of the material in the discretized area, at which the structure has maximum rigidity, taking into account the specified additional constraints. The mathematical formulation of the method is detailed in the work of M P Bendsoe and N Kikuchi [1].

2. Material and Limitations
The bracket is made of aluminum alloy AlSi10Mg. The material properties are shown in table 1. It is necessary to redesign the original bracket, reducing its weight, while the stress-strain state that occurs in the product during its operation should not lead to the destruction of the part. To ensure the strength of the bracket in the new version, when performing optimization, an additional restriction on the stresses arising in the bracket is used - the stress intensity according to von Mises, taking into account the safety factor, should not exceed 185 MPa at the design load.

| Yield Strength, MPa | Young's modulus, GPa | Density, g/cm³ |
|---------------------|----------------------|---------------|
| 275                 | 76                   | 2.67          |

Table 1. Material properties.

Topological optimization is impractical to carry out on the original geometry proposed by the designer, because the solver will be seriously limited in the choice of possible options for the mass distribution and will not be able to obtain the maximum possible rigidity of the structure. To increase the possible options for the final topology, it is necessary to expand the computational domain, for which the initial volume of the original geometry increases, while the enlarged computational domain should not intersect with other parts located in the assembly next to the redesigned bracket as part of the finished product. The initial geometry of the bracket (hereinafter referred to as Initial) and the extended computational domain are shown in figure 1.
The bracket is bolted to the base at three locations (green areas in figure 1a). The load on the bracket is transmitted through the central fasteners. For the bracket, the work considers three independent loading options (table 2), each of which is characterized by a certain direction and magnitude of the resulting force.

Table 2. Force Loading options

| No. | Px, N | Py, N | Pz, N |
|-----|-------|-------|-------|
| 1   | 0     | 800   | 1000  |
| 2   | 700   | 500   | 700   |
| 3   | 1500  | 0     | 0     |

After the completion performing of the topological optimization algorithm, a topology is obtained that must satisfy all three specified options for loading the bracket, as well as the specified restrictions on the mass of the part and the magnitude of the stress intensity. Due to the discrete finite element representation of the design area, automated or manual refinement of the optimization result is required by smoothing, repairing and refining the STL model in any CAD system (for example, by using the SpaceClaim system integrated in ANSYS), after which it becomes possible to perform verification strength calculations using the final topology.

Note that after topological optimization, complex-shaped products with many curved surfaces are obtained, the manufacture of which is complicated by the classical subtractive methods, additive technologies are often used, in particular, the selective laser melting (SLM) technology, which assumes the sequential layer-by-layer formation of the part (“bottom-up”) by fusion powder particles using a laser. The presence of surfaces hanging over the build platform requires the creation of a structure of supports that provide support for such surfaces at the stage of their formation, in addition, the presence of support structure provides better heat removal from the formed hot part, which ensures a better quality of the additive process, and also support structure act as an additional rigid frame, which does not allow the grown part to come off the build platform or collapse under the influence of significant internal stresses arising in the process of additive formation of the part. The disadvantage of such support structure is the increased consumption of powder spent on their manufacture, a longer process of manufacturing the part, the need to separate the supports from the final part after the completion of the technological process, as well as the need to perform additional operations for machining the points of attachment of support structure to the part, finishing the surfaces, taking into account the requirements for accuracy of geometry, roughness, etc. An urgent technological task is to manufacture a part without a support structure, however, in this case, the part must be redesigned for additive technology in such a way that its surfaces, for a given orientation of the placement of the part on the build platform, would be self-supporting, that is, the overhang angle between such surfaces and the build platform does not go out beyond predetermined limits. Further in the work we will assume that the surface is self-supporting and the creation of support structure for it is not required if the overhang angle between this surface and the build platform is more than 45°.

An example of a technique that allows you to take into account the restriction on the overhang angle is presented in [2], in which all the surfaces of the part are initially divided into self-supporting surfaces and not. Then an indicator is introduced that characterizes the proportion of self-supporting surfaces in the total number of surfaces of the part, after which the restriction on the value of this indicator is used in the formulation of the
topological optimization problem in the form of an additional constraint. The mathematical formulation of the problem used in this paper is presented in the equations (1)-(6): 

$$\min \, c(\rho) = U^TKU = \sum_{e=1}^{N} E_e(\rho)u_{e}^{T}k_{e}u_{e}$$  \hspace{1cm} (1)$$

$$E_e(\rho) = E_{\min} + (E_0 - E_{\min}) \cdot \rho_e^p(\rho)$$  \hspace{1cm} (2)$$

$$0 \leq \rho \leq 1$$  \hspace{1cm} (3)$$

$$K \cdot U = F$$  \hspace{1cm} (4)$$

$$V(\rho) \leq V_0$$  \hspace{1cm} (5)$$

$$\phi(\rho) \geq \phi_0$$  \hspace{1cm} (6)$$

where equation (1) is the condition for minimization of the compliance function, written using the well-known matrix formulations of the finite element method, equation (2) is an introduction to the virtual density optimization algorithm in the form of the Young's modulus law, equation (3) is the range of variation of the virtual density parameter, equation (4) is the constraint for the optimization problem, the fulfillment of which ensures the satisfaction of the equilibrium conditions when solving the solid mechanics problem, (5) is the constraint on the volume of the body after optimization, (6) is the condition on the proportion of self-supporting surfaces during optimization.

The procedure for topological optimization of the bracket, taking into account various requirements and constraints, was carried out further using the ANSYS package, Topology Optimization module.

3. Results and Discussion

Figure 2 shows the smoothed geometry of the bracket (hereinafter referred to as Topology 1), obtained after performing the topological optimization procedure, taking into account the restrictions on the final volume of the part and the maximum value of the von Mises stress intensity.

![Figure 2. Bracket model: (a) top view, (b) side view](image)

Figure 3 shows the fields of maximum displacements and stress intensity arising in the bracket under the most unfavorable loading case.

![Figure 3. Results: (a) stress, (b) displacement](image)
The resulting result shows that for given loading options and constraints on stresses and mass, it is sufficient to fix the bracket in only two places. It should be noted that the resulting geometric model has a significant number of surfaces for which the formation of support structure is required with the additive method of manufacturing a new part. Figure 4 shows the new geometry of the bracket (hereinafter – Topology 2), obtained by optimization taking into account the conditions for the formation of a topology containing mainly self-supporting surfaces.

Figure 4. Bracket model: (a) top view, (b) side view

Figure 5 shows the fields of maximum displacements and stress intensity arising in the bracket under the most unfavorable loading case.

Figure 5. Results: (a) stress, (b) displacement

As a result of the optimization, a part (Topology 2) is obtained that can be manufactured mainly without creating a support system. Due to the difference in manufacturing conditions, the final geometry of the bracket, in contrast to Topology 1, remains with three legs.

Let's compare all three parts – Initial, Topology 1 and Topology 2. The results of estimated calculations of the strength and stiffness of the three brackets are presented in table 3.

Table 3. Results.

| Geometry   | Mass, kg  | Max stress, MPa | Displacement, mm |
|------------|-----------|-----------------|------------------|
| Initial    | $4.367 \cdot 10^{-2}$ | 180.65          | 0.220            |
| Topology 1 | $1.578 \cdot 10^{-2}$ | 184.35          | 0.223            |
| Topology 2 | $4.282 \cdot 10^{-2}$ | 150.67          | 0.080            |

4. Conclusion
The results obtained demonstrate that topological optimization without constraints on the overhang angle of the surfaces of the part to the build platform turned out to be 64% lighter than the original model, without losing rigidity, which is provided by the SIMP topological optimization algorithm itself, in the frame of which,
for a given volume of material, topology is searched with the least pliability. The topology with self-supporting surfaces is close in mass to the original bracket, but with a stiffness of 2.75 times the original. During the design of the Topology 2 part, the task was not set to minimize the weight of the bracket as much as possible (table 3 shows that for Topology 2 the stress intensity limit has not yet been reached, there is potential for further weight reduction). The results obtained clearly show that when redesigning products using the SIMP topological optimization method, the designer has the opportunity to choose whether to ensure the greatest reduction in the weight of the product, or, at the same weight, due to the new topology, provide greater rigidity of the part in cases where it is necessary.

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**References**
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