Perspectives for organization of internal porous structure of loaded elements of optimal topology

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Abstract. The solution to the problem of topological optimization (TO) is often a complex irregular distribution of material. For this reason, the use of such results until recently was limited to theoretical studies. Modern additive technologies (AT) can solve this problem. A promising feature of AT is the possibility of obtaining a porous internal macrostructure of products. This can be used to optimize their mass during bending loads. In this paper, the problem of minimizing the compliance of a fixed two-dimensional beam is solved. The obtained structure was produced of ABS plastic according to the technology of layer-by-layer fusion of the material at different values of internal porosity. Standard three-point bending tests are implemented. It is shown that the use of porous products is a promising approach to reduce material consumption while maintaining the configuration of the stress-strain state. All other conditions being equal, these samples have greater plasticity and are capable of taking up large loads compared to monolithic products of the same mass.

1. Introduction

Additive technologies (AT) are one of the rapidly developing areas of industrial technology. They provide the creation of the finished product by adding material layer by layer. This is the main difference from traditional technologies, where the component is produced by removing excess material. AT allow you to overcome the limitations of traditional manufacturing techniques. This is due to the broadening of the range of used materials, increasing the accuracy and reliability of manufacturing, reducing the cost of equipment with an almost complete absence of technological limitations. Until recently, the application of AT was limited due to the high cost of equipment. Only in the last 5-10 years these technologies became available to consumers [1]. A detailed review of existing AT and their application is presented in [2].

The low cost and high reliability of FDM technology equipment (Fused Deposition Modeling - modeling by layer-by-layer fusion of extruded material) led to its wide distribution [3]. In this work, desktop 3D-printers were used for the manufacturing of prototypes, and a filament of ABS plastic was used as a consumable material.

AT represents an effective approach to the formation of finished products that have a number of advantages: production time decrease, processing tolerances minimization, ability to manufacture complex components obtained using topological optimization methods (TO) [4]. These circumstances, as well as the development of AT, providing the possibility of manufacturing complex ordered internal structures of products [5], determine the relevance of this study.
FDM technology provides the possibility of manufacturing the products with different internal filling, often of a regular structure, which can be set at the stage of task preparation for a 3D printer. The type of internal structure and the percentage of filling strongly influence on both the manufacturing process and the mechanical properties of the obtained product [6]. In general, a higher percentage of filling provides greater strength with increasing material consumption and production time. The interest in the use of porous materials continues to grow in areas where it is urgent to reduce the mass of products, for example, when creating new designs of unmanned aerial vehicles [7]. The porous structure also has good dynamic efficiency, lower requirements for manufacturing accuracy, corrosion resistance, high thermal resistance, and lower cost compared to traditional materials [8]. Therefore, the urgent task is to find a reasonable compromise between the mass of the product and its mechanical properties, which can be achieved by optimizing the internal structure.

The perspective of this direction is also confirmed by the organization of natural structures. There are samples with high resistance to bending, but with low weight, for example, animal bones and plant stems, which have a hard cover and a softer, often porous core.

2. Problem formulation

As an object of the study, we used the results of TO of the well-known Messerschmitt-Bölkoff-Blohm test problem (MBB) on the bending of a beam [9] (see figure 1, a). The length of the beam is \( L = 300 \) mm, height \( H = 50 \) mm, thickness \( t = 2 \) mm. The module of elasticity of the material of the beam is \( E = 7,1 \times 10^{10} \) Pa, Poisson's ratio \( \mu = 0,33 \). The beam movement is limited vertically at the lowest points. An external force \( P \) of 40 N acts dotty on the top edge in the middle of the beam. Since the geometry of the beam and the load scheme are symmetric, the analysis was carried out for a half-beam model (see figure 1, b). In the plane of symmetry there is no movement along the normal: \( u_x = 0 \). Fixing the lowest point on the movable bearing meets the boundary condition: \( u_y = 0 \).

![Figure 1. MBB Beam Load Diagram](image)

At TO stage, it is necessary to find the best distribution of material in a given area in terms of the hardness of the structure. Achieving the maximum hardness is equivalent to minimization of the system compliance [10]. In the case of a point load, the compliance is determined according to the expression

\[
C = \sum_{i=1}^{n} P(i) \cdot u(i),
\]  

where \( P(i) \) – external force vector acting at \( i \) point, N;  
\( u(i) \) – movement vector of \( i \) point, m;  
\( n \) – number of points to which external forces are applied.

In the considered problem, the external force acts at one point, causing it to move along \( y \) axis, therefore, the optimality criterion of TO task is simplified to the following:

\[
C = \frac{P}{2} u_y(0, H).
\]  

In the classical formulation of the problem TO use a limit on the mass of the material, which in this example is assumed to be 25% of the original value.
3. **TO task solution**

TO task is set as two-dimensional task. Discretization of the computational area was carried out using a finite element mesh. SIMP method [11] was used to solve the problem; the magnitude of the penalty coefficient was \( p = 3 \). The method of optimization is the method of globally converging MMA movement asymptotes [12]. The result of solving TO problem is the relative density field in the range of values from 0 to 1, which is shown in figure 2.

![Figure 2. Relative density field.](image)

A study for the influence of the porosity of the material on the strength of the product was conducted for the found geometry. The actual mass of this beam was 29.7% of the initial value.

4. **Sample making**

The samples were made on Hercules 3D printer using BestFilament ABS plastic for research. Using the display method developed by the authors [13], the results of TO beam were imported into Compass-3D CAD systems, where the complete solid-state three-dimensional model was constructed using the specular reflection method (figure 3). Due to the limitations of the print area of the printer (20x20 cm), the model was scaled proportionally along the x and y axes with a factor of 0.8 (length 240 mm, height 40 mm). The thickness of the model is increased to 10 mm for ease of further testing. We note that these transformations do not affect the product topology obtained at the stage of TO task solution.

Next, the geometry was exported to the standard .stl format used to create the control program. The formation of the printer control G-code was carried out in the system Slic3r [14]. The sample was located on the printable area diagonally, which ensured maximum size and favorable printing conditions. The samples were made with different porosity \( \xi \): 10, 30, 50, 70 and 100%. In this case, the fill of the inner and outer areas was implemented in a straight line pattern. The outer edges were made solid, so the differences of the samples are observed only in the internal structure of the products (figure 4).

![Figure 3. Solid state model of the sample with control points for the study of hardness.](image)
5. Experimental studies

Experimental studies involved the performance of a standard test for three-point bending. The determination of the characteristic loads of the samples was carried out on Testometric M350-5AT testing machine. The samples were placed on a base of 228 mm, test speed of 1 mm / min.

Considered constructions are ductile. As can be seen from figure 5, the destruction of samples occurs gradually: loss of strength is observed in the upper horizontal sections.

Figure 4. Samples with different values $\xi$: a – 10%, b – 30 %

Figure 5. Sample destruction results
a – loss of strength of the sample c $\xi = 100%$; b – place of sample destruction c $\xi = 50%$

Figure 6 shows the dependences of the force on the loading roller on its displacement for the studied samples taken during the experiment.

Figure 6. Results of three-point bending of samples.
As can be seen from figure 6, the internal porosity has a significant effect on the strength of the samples. The maximum load (about 550 N) takes a monolithic sample. A similar result (about 525 N) shows a sample with a porosity $\xi = 70\%$. The stress-strain state of the samples $\xi = 70\%$ and $\xi = 50\%$ is similar. The least durable sample is $\xi = 10\%$, its destruction is observed at 350 N.

6. Verification of efficiency of porous filling method for loaded bending structures

As noted above, the main purpose of creating an internal porous structure is to reduce the mass of products underwent bending. The increase in the proportion of empty spaces is inevitably accompanied by a decrease in the hardness of the structure. The experiments do not allow making an unambiguous conclusion about the effectiveness of the porous filling method from the point of view of minimizing the mass. The sample was made with 100% filling, equivalent to the mass of the sample with 10% filling to verify the effectiveness.

![Figure 7. Topology of solid sample, equivalent to the mass of porous sample with 10% filling.](image)

The density of used ABS plastic comprises 1050 kg/m$^3$. The mass of the sample with 10% filling is 20.91 g. Consequently, the volume of the plastic was 1.99 $10^{-5}$ m$^3$ or 20.7% of the volume of the optimized beam. TO task is re-solved with this value of the restriction on the volume of the material. The density field is shown in figure 7. The theoretical mass of the sample was 20.85 g, the actual mass was 21.21 g, which with high accuracy (98.6%) corresponds to the specified equivalence condition.

Figure 8 shows the experimental dependence of the force on the loading roller on its displacement for the sample with $\xi = 10\%$ (control) and the sample from figure 3 (monolithic).

![Figure 8. Results of three-point bending of the sample.](image)

As can be seen from figure 8, the control sample experiences movement of about 5 mm until the moment of durability loss with a force of 350 N on the loading roller. A monolithic sample withstands significantly smaller displacements (about 3 mm) with a load of 170 N. The average hardness of the
monolithic sample in the range of movements from 0 to 2.6 mm was 55 N/mm, and the hardness of the control sample was 82 N/mm.

7. Results and Discussion
The results of experimental studies (figure 6 and 8) show the possibility of reducing the mass of products of the optimal topology, obtained at the stage of solving TO problem. In the above example, the use of internal porous structure made it possible to increase the hardness of the product by 1.5 times. When analyzing the experimental data, it is necessary to take into account subjective factors that influence the quality of the obtained products. The following may be mentioned among them [15]:

1) differences in the properties of plastics from different manufacturers (this is true even for multi-colored plastics of the same manufacturer);
2) printing parameters (for example, temperature in extruder) affecting the structure and properties of the produced samples;
3) structure of 3D printers and their main components, providing a different positioning of executive mechanisms;
4) plastic storage conditions.

In this work, a rectangular pattern is applied to fill the internal sample volumes. It should be noted that Slic3r can generate other schemes: linear, concentric, Hilbert curves, cellular, Archimedes chords, and octagram spirals.

8. Conclusion
The conducted studies have shown the relevance of the adaptation of TO methodology to the features of AT to increase the efficiency of structures under the influence of bending loads. Despite all the advantages of AT, they are still a developing direction. Traditional manufacturing methods (turning and milling, injection molding, etc.) still dominate the manufacturing industry. Therefore, we can conclude that TO task must be formulated and solved taking into account the characteristics and restrictions of the selected AT in order to obtain suitable topologies for manufacturing [16]. It should be noted that recent research [17] pays attention to the solution of this issue, for example, it is possible to introduce into the formulation of TO task restrictions reflecting the features of the manufacturing process. This guarantees the possibility of manufacturing the considered products by the claimed method. In some cases, this affects the stage of preparation of process equipment: for example, you can eliminate the need for optical correction of photolithographic equipment. Nevertheless, additional studies in this direction are relevant.

When formulating directions for further research, the authors consider it as a relevant task to search for the optimal internal structure (pore size and shape) of structures subjected to bending.

The results of solving the problem of a TO beam subjected to bending suggest that the optimal topology represents fractal geometry: each element of the beam is similar to the previous one (larger).

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References
[1] Jones R, Haufe P, Sells E, Iravani P, Olliver V, Palmer C and Bowyer A 2011 RepRap – the replicating rapid prototyper Robotica 29 177
[2] Gibson I, Rosen D and Stucker B 2015 Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing (New York, NY: Springer New York)
[3] Wittbrodt B T, Glover A G, Laureto J, Anzalone G C, Oppliger D, Irwin J L and Pearce J M 2013 Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers 23 713

[4] Ivanova A O, Zavodov A V, Dynin N V and Fomina M A 2017 Efficiency of complex alloying AlSi10Mg type alloy with transition metals for selective laser melting technologies Proc. VIAM 1–1

[5] Cheng L, Liu J, Liang X and To A C 2018 Coupling lattice structure topology optimization with design-dependent feature evolution for additive manufactured heat conduction design Comput. Methods Appl. Mech. Eng. 332 408

[6] Wu J, Aage N, Westermann R and Sigmund O 2018 Infill Optimization for Additive Manufacturing-Approaching Bone-Like Porous Structures IEEE Trans. Vis. Comput. Graph. 24 21127

[7] Ferro C G, Brischetto S, Torre R and Maggiore P 2016 Characterization of ABS specimens produced via the 3D printing technology for drone structural components Curved Layer. Struct. 3 172

[8] Robbins J, Owen S J, Clark B W and Voth T E 2016 An efficient and scalable approach for generating topologically optimized cellular structures for additive manufacturing Addit. Manuf. 12 296

[9] Bulman S, Sienz J and Hinton E 2001 Comparisons between algorithms for structural topology optimization using a series of benchmark studies Comput. Struct. 79 1203

[10] Bankoti S, Jain N and Misra A 2015 Topological Optimization of 3D Structures by Optimality Criteria using ANSYS Int. J. Res. Emerg. Sci. Technol. 2 30

[11] Bendsoe M P and Sigmund O 2004 Topology optimization by distribution of isotropic material Topology Optimization (Berlin, Heidelberg: Springer Berlin Heidelberg)

[12] Svanberg K 2002 A class of globally convergent optimization methods based on conservative convex separable approximations Soc. Ind. Appl. Math. 12 555

[13] Alekhin P A, Glebov A O, Karpov S V, Karpushkin S V and Khlebnikov V A 2019 Development of an Algorithm for Displaying the Topological Optimization Results in Two-Dimensional Problems of Stationary Heat Conduction Transactions TSTU 25 22

[14] Anon Slic3r - G-code generator for 3D printers

[15] Tymrak B M, Kreiger M and Pearce J M 2014 Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions Mater. Des. 58 242

[16] Liu J and Ma Y 2016 A survey of manufacturing oriented topology optimization methods Adv. Eng. Softw. 100 161

[17] Lazarov B S, Wang F and Sigmund O 2016 Length scale and manufacturability in density-based topology optimization Arch. Appl. Mech. 86 189