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TOPOLOGY OPTIMIZATION METHOD FOR IMPROVING THE MASS EFFICIENCY OF ALUMINUM BEAMS

Abstract: *In this study, an investigation was carried out to reduce the mass of a cantilever beam made of Al9 aluminum alloy using topology optimization (TO) based on the SIMP method. The optimization was performed with the APM FEM software package, which made it possible to implement numerical modeling at a modern level, taking into account the material features. The beam was subjected to a combined action of a concentrated vertical force of 4000 N and a longitudinal tensile force of 3000 N, which allowed simulating an actual operating load close to the working conditions of structures in mechanical engineering and construction. During the calculations, it was possible to reduce the mass of the structure by 52% while maintaining the main strength characteristics. At the same time, an increase in maximum stresses compared to the initial model was observed, which is associated with the redistribution of material and stress concentration in certain zones. However, the stress level remained within values close to those permissible for the chosen material considering the safety factor. Modal analysis confirmed sufficient separation of natural frequencies from critical values. The obtained results demonstrate the potential of applying TO for the design of lightweight, energy-efficient, and technologically promising structures.*

Key words: *topological optimization, shape optimization, aluminum, beam, casting, finite element method, optimal design, microhardness, mass efficiency.*

Introduction

Manufacturing industries such as automotive and aerospace engineering are continuously evolving, implementing new technologies to enhance the performance characteristics of components. One of the most desirable outcomes for these industries is a significant reduction in component weight. A promising approach to weight reduction lies in the design process at the early stages of product development. The creation of lightweight structures is a priority in modern engineering problems, as reducing the weight of load-bearing elements contributes to increasing the payload ratio, decreasing material consumption in production, and improving energy efficiency – especially in systems with moving functional components.

Topological optimization (TO) is a modern and efficient design method aimed at determining the optimal material distribution within a given design domain under specific constraints [1-4]. The primary goal of TO is to minimize the mass and cost of a product while maintaining its strength and stiffness characteristics. This approach is particularly relevant in the context of the rapid development of manufacturing industries, where lightness, cost-effectiveness, and high structural efficiency are of great importance.

Among the various topological optimization methods, the Solid Isotropic Material with Penalization (SIMP) method [5-7] has gained the widest application. It is characterized by mathematical simplicity, versatility, and the ability to be implemented in popular engineering software packages. The SIMP method is based on using material density as a variable, which enables flexible control over the material distribution within the computational domain. Each finite element in the mesh is assigned a relative density in the range from 0 to 1, determined by its contribution to the overall stiffness of the structure.

The application of the SIMP method has been integrated into commercial software solutions such as TOSCA (ABAQUS), GTAM (ANSYS), Inspire (Altair), and APM StructFEM (KOMPAS-3D), allowing engineers and designers to easily incorporate TO into existing workflows. Despite the presence of intermediate density values, modern algorithms and visualization technologies (e.g., isosurface-based methods) make it possible to convert such regions into manufacturable solid geometries.

Unlike the BESO method, where densities take only discrete values (0 or 1), the SIMP approach provides a more precise and detailed material distribution, which is particularly important for designing lightweight yet strong structures. This makes the SIMP method especially attractive for the development of geometrically complex components.

In addition, recent years have seen active development in the creation of lattice structures, which allow a significant reduction in the weight of a product without compromising its strength [8]. The integration of lattice cells with TO results obtained using the SIMP method has found wide application in fields such as biomedicine, automotive, and aerospace industries. Software packages such as nTopology and Autodesk Netfabb already provide tools for generating optimized lattice structures tailored to specific load conditions.

Thus, the use of the SIMP method in topological optimization problems of structural elements is a justified and effective approach that enables the development of lightweight, strong, and manufacturable structures, as confirmed by the results obtained in this study.

Topological optimization represents a method of structural design aimed at the rational distribution of material within a constrained computational domain. This distribution is carried out considering external loads, boundary conditions, and permissible constraints [9–12]. The solution to such problems is generally based on the finite element method, within which each mesh element is assigned a density parameter that determines its contribution to the overall stiffness of the structure. The result of topological optimization is a material density distribution that forms a structure with minimal mass while maintaining the required mechanical characteristics. Objective functions and constraints may include such parameters as compliance, strain energy, volume, displacements, and strength characteristics.

Today, topological optimization is actively used in various engineering industries, including aerospace, automotive, and energy sectors, where reducing weight and increasing structural reliability are of paramount importance. In this study, topological optimization is applied to a cantilever beam subjected to a concentrated vertical load of 4000 N and an axial tensile force of 3000 N at the free end. The main objective is to reduce the structural mass while maintaining its functional and mechanical performance, including strength and stability.

Materials and Methods

The objects of topological optimization in this study are aluminum beams made of Aluminum Al 9 (analogous to AlSi9Cu or A356 in international standards by ASTM B26 / B108). These elements are subjected to operational loads during service, including bending, compression, and vibration.

The beams may also experience localized heating due to external factors or friction in mating components. In addition to their load-bearing function, they partially participate in heat dissipation, ensuring thermal stability of the structure. The design of the beams must provide sufficient strength and stiffness while maintaining minimal mass, which makes the application of topological optimization particularly relevant.

In this study, a cantilever beam made of Aluminum Alloy Al9 with a rigidly fixed end was considered. Two loads were applied to the free end of the beam: a concentrated force of 4000 N directed vertically downward along the Y-axis, simulating a bending moment, and an axial tensile force of 3000 N acting along the X-axis of the beam. This loading scheme made it possible to simulate the combined effect of bending and tension, which is typical for many structural components under real operating conditions.

The forces were applied at a single point on the free end of the beam. The vertical load caused bending in the XY-plane, while the axial tensile force produced longitudinal stretching of the structure.

The material characteristics employed in the computational analysis are summarized in Table 1.

Table 1 – Material properties of aluminum beams

Part №	Material properties							
	Material Grade	Density, kg/m³	Elastic Modulus, GPa	Poisson's Ratio	CTE, 1/K	Specific Heat Capacity, kJ/(kg·°C)	Thermal Conductivity, W/(m·K)	Ultimate Tensile Strength σ, MPa
1	Al-9	2780	70	0,33	23,5 10^{-6}	0,88	170	260
2	Al-9	2780	70	0,33	23,5 10^{-6}	0,88	170	260

With a safety factor of 2.5, the allowable stress level for the Al9 alloy is 100 MPa. The topological optimization task was carried out using the KOMPAS-3D software package. Figure 1 shows the initial models, loading conditions, and boundary constraints.

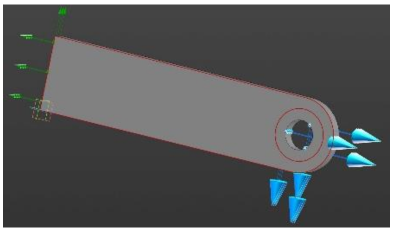
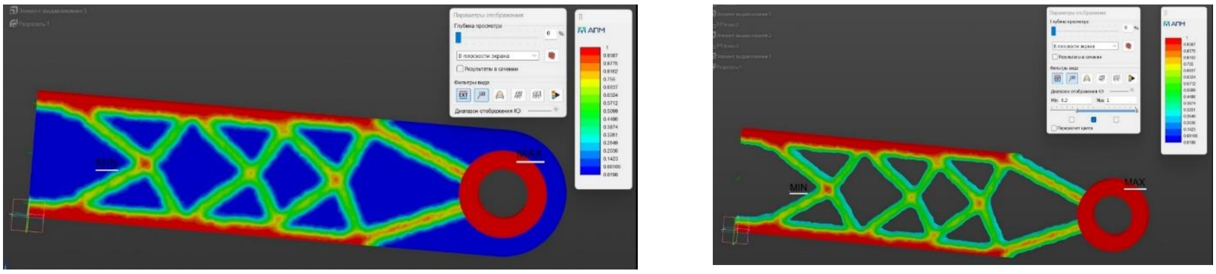


Figure 1 – Cantilever beam model subjected to concentrated loads of 4000 N (Y) and 3000 N (X) at the free end

In the optimization parameters, the target mass reduction was set to 50-70%. Based on the calculations, the optimal topology of the solid component was obtained. The results of the topological optimization, showing the material density distribution, are presented in Figure 2. In the image, the red regions correspond to areas of maximum material density, while the blue regions indicate areas of minimum density.

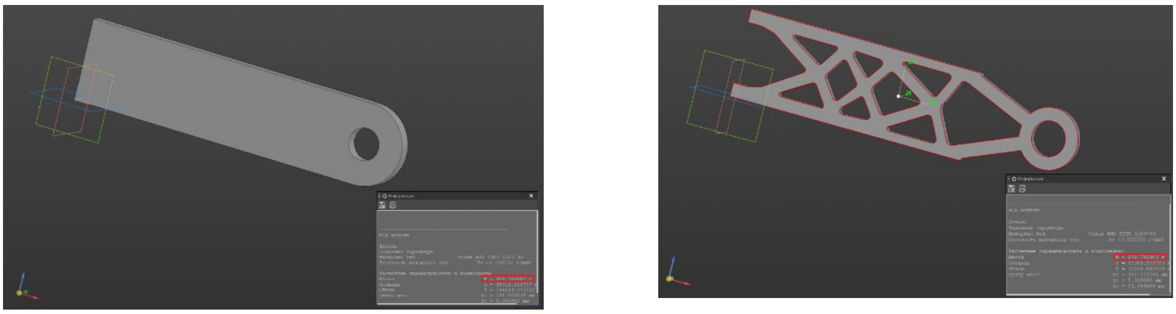


a) *b)*

Figure 2 – Topological optimization results:
a) regions subjected to optimization; b) final optimized structure.

The optimization was carried out using APM FEM, which implements an approach similar to the SIMP method. During the formation of the optimal geometry, solid elements with varying thicknesses and internal cutouts were modeled. Figure 3 presents the resulting optimized structure. The thickness in the marked area is 2 mm. As a result of the optimization, the mass of the component was reduced by approximately 20%.

Figure 3 shows the initial geometry of the original and the optimized beams. The original beam was used as the baseline model for subsequent topological optimization.



a) *b)*

Figure 3 – Beams and their masses:
a)original beam; b) optimized beam.

Figure 4 presents the stress analysis results for the original component under bending loads. The maximum stress reached 1375.6 kgf/cm² (≈137.5 MPa), which corresponds to the expected values for a structure with this level of stiffness.

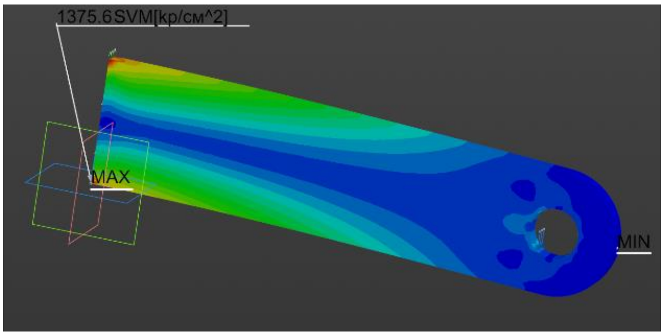


Figure 4 – Distribution of stresses in the initial beam under bending load

Figure 5 illustrates the stress distribution in the topologically optimized structure. The maximum stresses increased to 1561.3 kgf/cm² (≈156.1 MPa), which is associated with the redistribution of material and the appearance of stress concentration zones in the remaining load-bearing elements.

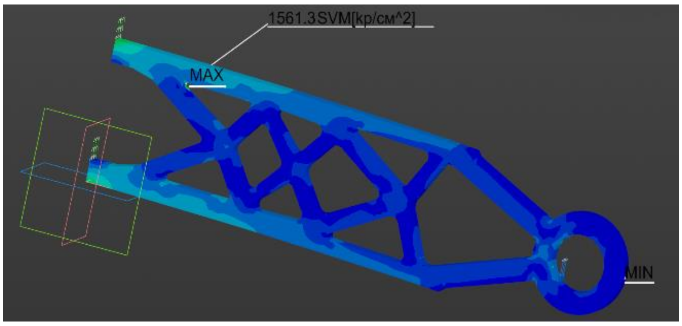


Figure 5 – Distribution of stresses in the topologically optimized beam

Results and Discussion

The results of the conducted topological optimization are presented in Tables 2 and 3.

Table 2 – Results of Topology Optimization. Mass

Initial mass, g	Mass after optimization, g	Mass reduction, %
368,8	178,8	51,5

Table 3 – Results of Topology Optimization. Stress

Stress in the initial part, MPa	Stress in the optimized part, MPa
137,5	156,1

The obtained stress distribution data reflect the influence of the combined bending and tensile loads. The maximum stresses are observed in the beam's fixed region, where the main internal forces are concentrated.

The analyzed components were manufactured by conventional casting from the Al9 aluminum alloy. This alloy was selected due to its good casting fluidity, stable mechanical properties, and widespread use in mechanical engineering. Al9 is an analogue of commonly used casting alloys such as AK9 and ML5, possessing a similar chemical composition, which ensures a comparable level of strength and reliability in operation.

As a result of the conducted topology optimization, the mass of the parts was reduced by 20-52%. At the same time, the maximum stress values in the optimized structures remained at a level comparable to that of the initial models before optimization.

Figures 3-5 present the geometries and strength analysis results for the initial and optimized beams. As can be seen, despite a significant reduction in structural mass (from 368.8 g to 178.8 g), the stress level remains within the permissible range. The topologically optimized beam, however, exhibits a more complex stress distribution with local concentrations in the areas where the lattice elements intersect.

The Al9 aluminum alloy was selected as the main casting material due to its combination of good casting properties, availability, and stable mechanical characteristics. Its density is approximately 2780 kg/m³, making it similar to widely used aluminum alloys such as AK9 and AlSi10Mg. Unlike the magnesium alloy ML5, which has a lower density (1810 kg/m³), aluminum alloys provide higher strength and stiffness – properties that are especially important when designing critical load-bearing components.

The use of Al9 is a justified choice, as it ensures the required structural strength at an acceptable weight and is well suited for traditional casting technologies. Furthermore, the operational performance of the parts can be enhanced by applying protective coatings using the micro-arc oxidation (MAO) method [14-15], which significantly improves the surface hardness, wear resistance, and corrosion resistance of aluminum alloys.

Thus, the use of Al9 alloy in combination with topology optimization and subsequent micro-arc oxidation surface treatment provides a rational balance between structural strength, weight, and durability.

Conclusion

The results of the performed optimization can be summarized as follows:

– The component mass was reduced by 20-52 %;

– The use of the Al-9 aluminum alloy was found to be justified due to its favorable combination of strength, castability, and manufacturability;

– The natural frequencies of the structure were tuned to be 10-20% away from critical values;

– The strength characteristics were maintained despite the optimized geometry;

– It should be noted that in this study, the stress levels exceed those corresponding to the required safety factor, which is due to the demonstration nature of the research and geometric limitations of the model. Further refinement of the geometry can be performed in future work to account for this factor.

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МЕТОД ТОПОЛОГИЧЕСКОЙ ОПТИМИЗАЦИИ ДЛЯ ПОВЫШЕНИЯ МАССОЭФФЕКТИВНОСТИ АЛЮМИНИЕВЫХ БАЛОК

В данной работе проведено исследование, направленное на снижение массы консольной балки из алюминиевого сплава Ал9 с применением топологической оптимизации (ТО) на основе метода SIMP. Оптимизация выполнялась с использованием программного комплекса APM FEM, что позволило реализовать численное моделирование на современном уровне с учётом особенностей материала. Балка испытывала комбинированное действие сосредоточенной вертикальной силы 4000 Н и продольной растягивающей силы 3000 Н, что позволило смоделировать реальную эксплуатационную нагрузку, близкую к условиям работы конструкций в машиностроении и строительстве. В процессе расчётов удалось снизить массу конструкции на 52 % при сохранении основных прочностных характеристик. При этом наблюдалось увеличение максимальных напряжений по сравнению с исходной моделью, что связано с перераспределением материала и концентрацией напряжений в отдельных зонах конструкции. Однако уровень напряжений остался в пределах, близких к допустимым для выбранного материала с учётом коэффициента запаса прочности. Проведён модальный анализ подтвердил достаточную отстройку собственных частот от критических значений. Полученные результаты демонстрируют потенциал применения ТО для проектирования облегчённых, энергоэффективных и технологически перспективных конструкций.

Ключевые слова: *Топологическая оптимизация, оптимизация формы, алюминий, балка, отливка, метод конечного элемента, оптимальное проектирование, микротвердость, массоэффективность.*

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АЛЮМИНИЙ АРҚАЛЫҚТАРЫНЫҢ МАССАЛЫҚ ТИІМДІЛІГІН АРТТЫРУҒА АРНАЛҒАН ТОПОЛОГИЯЛЫҚ ОҢТАЙЛАНДЫРУ ӘДІСІ.

Бұл жұмыста Al9 алюминий қорытпасынан жасалған консольді арқалықтың массасын азайту мақсатында SIMP әдісіне негізделген топологиялық оңтайландыру (ТО) қолданылып зерттеу жүргізілді. Оңтайландыру APM FEM бағдарламалық кешенінің көмегімен орындалды, бұл материалдың ерекшеліктерін ескере отырып қазіргі деңгейде сандық модельдеуді іске асыруға мүмкіндік берді. Арқалыққа 4000 Н тік бағытталған күш пен 3000 Н бойлық созу күші әсер етті, бұл машина жасау және құрылыс салаларындағы құрылымдардың жұмыс жағдайларына жақын нақты жүктемені модельдеуге мүмкіндік берді. Есептеулер нәтижесінде негізгі беріктік сипаттамаларын сақтай отырып, құрылымның массасын 52 %-ға азайту мүмкін болды. Сонымен қатар, бастапқы модельмен салыстырғанда максималды кернеулердің артуы байқалды, бұл материалдың қайта бөлінуімен және кейбір аймақтардағы кернеу концентрациясымен байланысты. Алайда кернеу деңгейі таңдалған материал үшін беріктік қоры коэффициентін ескере отырып, рұқсат етілген мәндерге жақын болып қалды. Жүргізілген модальды талдау меншікті жиіліктердің сындарлы мәндерден жеткілікті қашықтықта екенін растады. Алынған нәтижелер ТО әдісін жеңіл, энергия үнемдейтін және технологиялық тұрғыдан болашағы бар құрылымдарды жобалауда қолданудың әлеуетін көрсетеді.

Түйін сөздер: *Топологиялық оңтайландыру, пішінді оңтайландыру, алюминий, балка, құю, соңғы элементтер әдісі, оңтайлы жобалау, микрокаттылық, масса тиімділігі.*

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ВЛИЯНИЕ ЭЛЕКТРОЛИТНО-ПЛАЗМЕННОЙ ЗАКАЛКИ НА СТОЙКОСТЬ СТАЛЕЙ МАРКИ 45 И 65Г К АБРАЗИВНОМУ ИЗНАШИВАНИЮ

Аннотация: *В данной работе представлены результаты экспериментального исследования влияния электролитно-плазменной закалки (ЭПЗ) на изменение микроструктуры, микротвёрдости и стойкости к абразивному изнашиванию широко применяемых конструкционных сталей марок 45 и 65Г. Обработка проводилась в электролите на основе водного раствора карбоната натрия при напряжении 300-320 В и времени воздействия 2-3 секунды. Метод ЭПЗ обеспечивал сверхвысокие скорости нагрева и последующего охлаждения за счёт прямого контакта с электролитом, что способствовало формированию тонкого упрочнённого слоя с мартенситной структурой и карбидными включениями.*

Результаты микроструктурного анализа показали наличие трёх характерных зон: закалённого слоя, зоны термического влияния и неизменённой матрицы. Микротвёрдость поверхности после ЭПЗ возросла в 1,6-1,8 раза по сравнению с исходным состоянием, а стойкость к абразивному износу – в 1,3-1,6 раза. Отмечается положительное влияние увеличения