Load carrying capacities of gears with a lattice structure body

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Abstract. Lattice structures are type of topology structures that have complex geometry, composed of multiplicated unit cells through which a pattern is generated. Lattice structures are of great interest in engineering due to their strength-to-weight ratio. There has been an increasing trend for their application as infill patterns in a variety of engineering parts and elements. However, the complexity of the lattice geometries, makes them difficult to be produced by conventional methods. Therefore, additive manufacturing technologies have been used as technologies for production of parts containing lattice structures. In this research, the focus is placed on analyzing various unit cell structures and their application in conventional gears as their structure body. One specific lattice structure is chosen and generated. Several characteristics of the lattice structure can vary, like the cell size, density, wall thickness etc. The lattice shape will remain the same for all the analysis. The lattice is optimized by weight reduction and maintaining load carrying capacity of the gears. Different samples are examined using FEM (Finite Element Method) in terms of determination the load carrying capacity. The results for the optimized gear body structures are elaborated, conclusions are drawn and recommendations for application of gears with a specific lattice structure are provided.

1 Introduction

Cellular or lattice structures and additive manufacturing (AM) represent a powerful combination that has transformed the way we design and manufacture objects. These technologies offer immense potential for creating lightweight, strong, and functionally optimized components across a wide range of industries.

Cellular structures are abundant in nature and can be found in various organisms and materials, such as the honeycomb structures, sponge skeletons, bone trabeculae, plant parenchyma cells, etc. By drawing inspiration from these natural cellular structures, engineers have been developing structures and materials that exhibit similar characteristics. Foams are one type of modern technical materials that have a cellular architecture. Metal foams, for example, are generated using alloy combinations, treating them with regulated heating processes and including a pre-treated foaming agent that releases gas [1]. As explained by [1], these type of metal foams are ideal for lightweight constructions due to a high stiffness-to-mass ratio compared to the corresponding dense materials. However, such cellular materials result with cell characteristics that are randomly obtained through the described processes, with no control over the cell sizes and arrangements [2]. Lattice structures, on the other hand, are a type of cellular structures which differ from foams due to their precise arrangement and periodic geometry that has a regularly repeating structure of the unit cell that it is composed of [2, 3]. Therefore, lattice structures are "architected cellular materials" that allow high control over their cellular structure and as a result, provide a method to generate the desirable mechanical properties of the material by simply modifying the geometry of the lattice (or lattice units) [2].

Lattice structures provide unique properties due to their geometry. The lattice framework allows for efficient material usage and is very light-weighing. These structures exhibit excellent mechanical and thermal properties, such as high strength-to-weight ratio, high strength and stiffness, improved energy absorption, enhanced load distribution, and high permeability [2, 3]. These properties make them ideal for application in multiple industries: biomedical, aerospace, sports, etc. The mechanical properties of the lattice structures are linked to (1) the mechanical properties of the parent material and (2) the type of lattice. The relative density of the lattice, which is expressed as a ratio of the density of the lattice and the density of the parent material, is directly dependent with the mechanical properties – as the relative density decreases, the mechanical properties of the lattice structure also decrease [3]. The mechanical properties also depend on the structure of the unit cells – "the size, type, orientation, and boundary conditions of the periodic unit cell" which can be designed to obtain specific mechanical properties [4].

Regarding the different types of lattices, that consist of different types of unit cells, they are mainly classified in three families: surface-based – generated from trigonometric equations, strut-based – consisted of rods (struts, or beams) and nods and planar based – created from extruded 2D planes [5]. Strut-based lattices have a

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simpler design and are defined by the Maxwell number (M) that depends on their number of struts and rods and if the M number is positive the structure is stretch-dominated (meaning that it is stiff and strong) [2, 3]. The surface-based lattices are triply periodic minimal surfaces (TPMS) and are bending-dominated, designed to distribute loads and forces across the lattice structure, effectively transferring bending stresses throughout the lattice framework. The most commonly used TPMS lattice is the gyroid which has a spherical core and circular, smooth struts, and is self-supporting [6, 7]. TPMS lattices, such as the gyroid, have potential advantages over other types of lattice structures. The presence of continuous curvature in gyroid lattices and absence of nodes in these architectures decreases stress concentration, leading to improved fatigue strength [2]. Gyroids exhibit nearly triple the specific energy absorption compared to strut-based structures of similar porosity [3]. In addition, TPMS lattices are easier to manufacture as a result of their continuous structure, which is another key benefit, especially since lattice structures are challenging to produce.

The complexity of the lattice geometries makes them impractical and impossible to be produced by conventional methods and they can be accurately produced only by additive manufacturing (AM) technologies. Unlike traditional subtractive manufacturing techniques that involve removing material from a larger block, AM builds physical objects from digital information layer-by-layer, a process which provides many design opportunities and benefits like: creation of complex, internal, freeform geometries; production of macro-structure topology optimized objects for reduced material; and creation of three-dimensional lattices and trusses with specific properties [4]. By using AM technologies, such as Powder Bed Fusion (PBF), Selective Laser Melting (SLM) or Electron Beam Melting (EBM), metal lattice structures for mechanical components can be efficiently fabricated. The processes vary, but they are all based on melting layers of metal powders. However, the precision of production also depends on the type of lattice. Research shows that lattice structures with gyroid unit cells have best manufacturability. As described by [7], “the inclination angle of the circular and smooth struts of the gyroid unit cell continuously varies along the spherical core, which makes layers grow up gradually” and “the previously manufactured layer can support next layer, the gyroid lattice structures are self-supporting”. In the research, using SLM process, gyroid lattice structures with a volume fraction of 15% and unit cell sizes ranging from 2 to 8 mm were successfully manufactured without any noticeable deformations. In another research [8], two gyroid lattices (Schoen Gyroid and Schwartz Diamond) were produced using SLM to investigate the manufacturability of the gyroid units with different cell sizes (2, 5 and 8mm). Results showed that all sizes were manufacturable through SLM – the 8 mm cell size with no deformation and the 2 mm cell size with no damage of struts. The fact that small cell sizes can be produced with no damage is a crucial aspect since smaller lattice cells have higher densities and relative densities and higher yield strength and Young’s modulus, thus better performance [7].

This newfound ability to generate complex design of mechanical components and produce them successfully with suitable AM methods has been highly advantageous for enhancing product performance across a wide range of applications.

In this research, our aim is to contribute to the expansion of knowledge regarding the methods of incorporating these lattice structures into machine components intended for larger machine assemblies, with the main goal of reducing the weight of the parts while maintaining the required mechanical characteristics. In this study, it was decided to apply surface-based, TPMS, gyroid lattice due to all the aforementioned advantages and to experiment with the characteristics of its unit cells, analyze the differences, and provide recommendations for implementation. The main research objectives are elaborated in greater detail in the following section.

2 Objectives

This research focuses on the application of lattice structures in conventional gears as their structure body. The emphasis is placed on optimizing the lattice structure for weight reduction while maintaining the load carrying capacity.

Reducing the weight and vibration of gears has been an important goal which leads to achieving improved performance, efficiency and longevity of gear systems. There are numerous researches that experiment with lattice structures to achieve this goal. Mainly, the application of lattices in gears is done through processes of topology optimization, according to Finite Element Analysis (FEA), which means optimizing the application of the lattice based on previously analyzed stress and strain distribution [9]. Another method is firstly selecting the lattice topology and replacing the solid with the lattice structure based on previous knowledge, continuing with homogenization of the lattice cell with the use of FEA, then applying a genetic algorithm to help define the strut diameter value for each cell, and in the end, evaluating obtained solutions, again using FEA [10]. For example, in the research of [11], a Ti spur gear with a cellular structure between the gear toothed ring and fixed hub, generated using a topology optimization software, was manufactured by the SLM process. The results showed reduced gear vibrations with the new gear design. The research of [12] presents a similar experimental approach for optimizing gears where a topology optimization software was applied to generate a lattice gear body, but the lattice was optimized further to remove stress concentrations and to reduce the stress levels. The research of [13], on the other hand, is based on the Michell Truss Method, rather than only a topology optimization, to design lightweight gears.

Although such researches in the field of lightweight gears cover the analysis of topology optimization methods and present performance results of the generated lightweight lattice gears, there is very limited information regarding the application of different types of lattice unit cells in gears, as well as cell variations. Therefore, this study aims to explore one specific lattice structure chosen for generating a lightweight gear body and the effects of changing the variable characteristics of that lattice. For this research, the gyroid lattice is chosen due to the multiple advantages it offers, as elaborated in existing literature, all of which are of great importance for the construction of gears: outperforming strut-based lattices on angular loads; better distribution of load; lack of stress concentration regions; increased fatigue life; etc. [14]. The characteristics of the TPMS, gyroid lattices were stated in various researches, as given in the introduction part, but the application of such a lattice precisely in gears was found in very little sources. The most similar approach to the one used in this research was found in the paper of L. H. Nguyen and K. T. Nguyen, 2022 [15] – where the mechanical properties of the gyroid structure applied to additive-manufactured plastic gears are explored. This research focuses on properties of metal gears, that can be produced by SLM.

The main objective of this study is to vary the approximate thickness, or unit cell thickness, of the Gyroid Faced Lattice applied as an infill in the gear body, and compare samples using FEM analysis to conclude which cell configuration results with maximum gear weight reduction while not compromising the required load carrying capacities.

The used methodology, procedure, results and conclusions are elaborated in the following sections.

3 Methodology

To assess the impact of lattice structures on the load carrying capacity of gears, a comprehensive analysis of four cases was conducted. Each case involved a different gear configuration, ranging from a solid gear, to gears with lattice structures of varying infill percentages and thicknesses. The first case served as the baseline, using a solid gear design. This traditional approach provided a reference point for comparing the subsequent cases. It represented a gear with a continuous, solid structure, without any lattice patterns or voids. Furthermore, the second case featured gears with a lattice structure, consisting of 60% infill and a thickness of 9.75 mm. In this configuration, the gear incorporated a lattice pattern with a relatively high infill percentage, ensuring a substantial amount of material within the structure. The increased thickness of 9.75 mm aimed to maintain the overall strength and rigidity of the gear. The third case, explored gears with a lattice structure comprising 40% infill and a thickness of 6.5 mm. This design sought a balance between weight reduction and structural integrity. By reducing the infill percentage and thickness, compared to the second case, the gear aimed to decrease its weight. In the fourth and final case, gears with a lattice structure featuring 20% infill and a thickness of 3.25 mm were examined. This design emphasized maximum weight reduction while still ensuring the gear's functional performance. The lower infill percentage and thinner lattice structure contributed to a significant reduction in

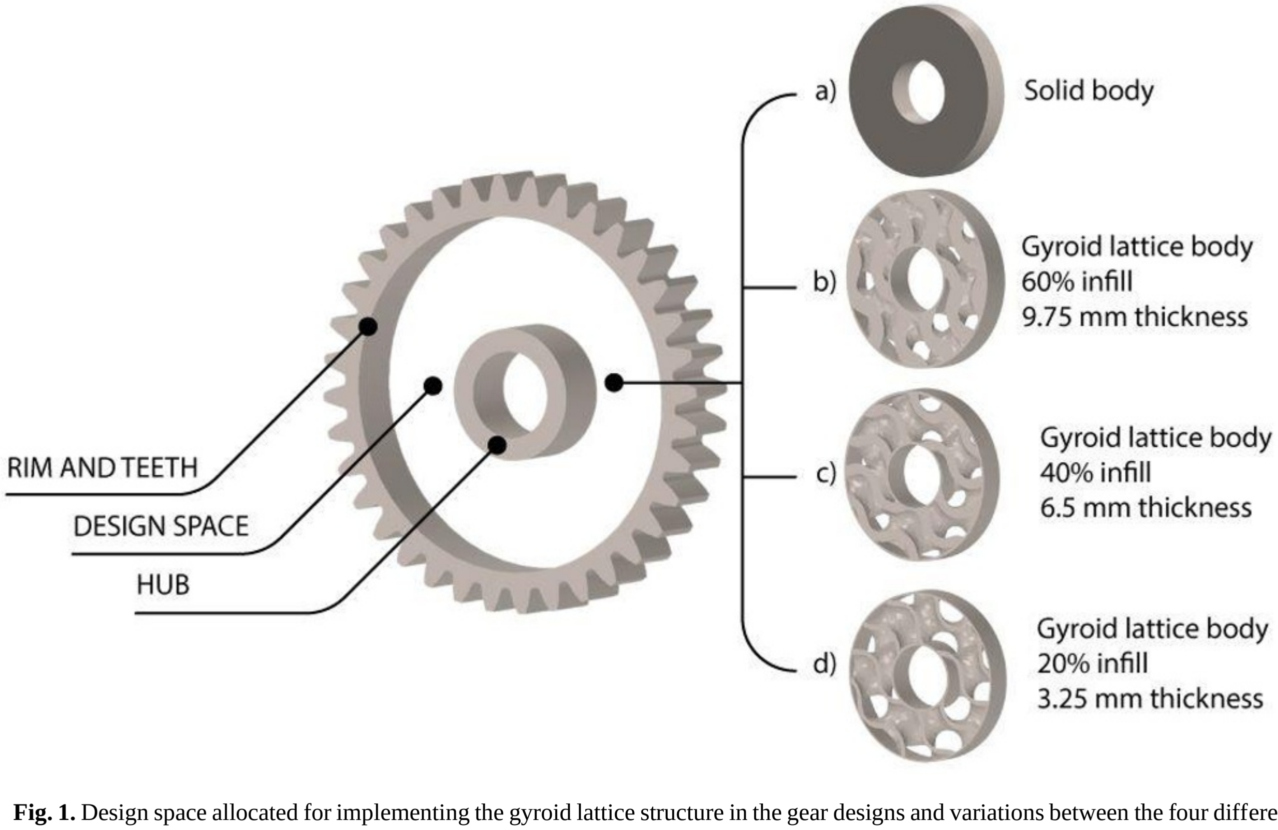

Fig. 1. Design space allocated for implementing the gyroid lattice structure in the gear designs and variations between the four different cases.

weight compared to the previous cases. By analyzing these four cases, the aim was to understand how the implementation of lattice structures with varying infill percentages and thicknesses impacts the load carrying capacity of gears.

Figure 1 illustrates the design space for implementing the lattice structure in the gears and shows the variations between the different infill amount and wall thickness.

All four cases of the analysis include gears with identical characteristics. The gears that are used, share same specifications, like module of 4 mm, pressure angle of 20 degrees and width of 20 mm. These consistent parameters ensure uniformity in size, tooth profile and gear geometry among all cases. The standardized characteristics neglect the gear production factors and include only the effects of the lattice structures on the load carrying capacity of the gears. Detailed specification of the gears parameters is given in Table 1.

Table 1. Specification of gear set.

Parameter	Pinion	Gear
Number of teeth	36	36
Modul [mm]	4	4
Pressure angle [°]	20	20
Pitch Diameter [mm]	144	144
Face Width [mm]	20	20
Material Young's module [N/mm2]	206 000	
Poisson's ratio	0.3	
Torque [Nm]	150	
Contact force [N]	2083	

FE analysis was conducted to assess the effects of the changed lattice structure on the load-carrying capacity of the gears. The focus were parameters such as contact pressure, root stress, stress in the body of the gear and total deformation.

Furthermore, an analytical calculation of the contact pressure was conducted following the guidelines outlined in ISO 6336-2:2006. This calculation was carried out to verify and validate the simulation results obtained from the FEA. According to ISO 6336-2:2006, the formula for calculating the nominal contact stress at the pitch point P, for flawless gearing (ideal gears, without errors), and because of the application of static nominal torque, is as follows [16,17]:

$$\sigma_{H0} = Z_H Z_E Z_\varepsilon Z_\beta \sqrt{\frac{F_t}{bd_1}\frac{u+1}{u}} \qquad (1)$$

Where,

Z_H - Zone factor
Z_E - Elasticity factor
Z_ε - Contact ratio factor
Z_β - Helix angle factor
F_t - Nominal tangential load
b - Face width
d_1 - Pitch diameter
u - Gear ratio

Detailed information on the calculation procedure for contact pressure can be found in [17].

4 FEM Analysis

FEM was conducted to understand the mechanical behaviour of involute spur gears with lattice structure bodies and varying lattice infill percentages. Four cases were analysed, which included: a solid gear, a gear with a lattice structure and 60% infill, a gear with a lattice structure and 40% infill, and a gear with a lattice structure and 20% infill. Figure 2 illustrates the gears in contact, where one gear was used as the test gear and its body was changed for every case, while the other gear remained solid and was used as contact gear. The 3D models for all cases were created using SolidWorks and Ansys Spaceclaim. After preparing the 3D models, they were imported into Ansys Workbench for the FEM analysis.

For all cases, consistent contact and boundary conditions were used. Bounded contact was defined between the Gear body and Rim, and between the Gear body and Hub, as shown in Figure 2. Additionally, frictionless contact was specified between the gears. Boundary conditions were applied to both gears in the analysis. A cylindrical support with no degree of freedom was defined on surface A (Figure 2), representing a fixed connection. On surface B (Figure 2), a cylindrical support with free rotation was defined, allowing the gear to rotate freely around its central axis. Additionally, a moment of 150 Nm was applied to surface B (Figure 2) to represent the applied load on the gears.

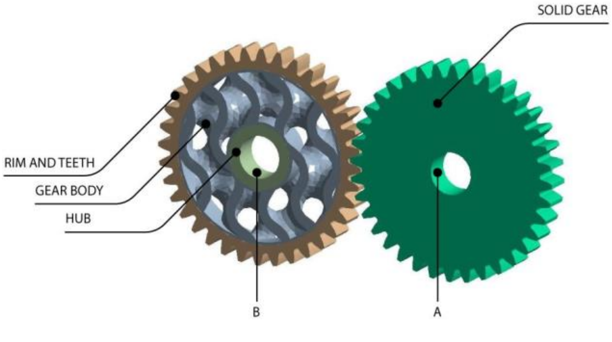

Fig. 2. Gears in contact (case with 40% infill).

A well-structured mesh is crucial to obtain accurate stress and deformation results in FEM analysis. Initially, an automatic mesh was created for the gears in all four cases. However, due to the complex geometry of the lattice structure, Ansys mesh control options were included to define a finer mesh in the contact zones between the gears and areas where stress concentrations were expected. This refined mesh was used to ensure precise stress analysis, particularly in critical regions. Because of the complexity of the lattice structure, tetrahedral elements were chosen for mesh generation, as shown in Figure 3. Tetrahedral elements are well-suited for handling complex geometries in FEM analysis.

Fig. 3. Mesh with tetrahedral elements for gears in contact (case with 40% infill).

5 Results and discussion

To investigate the influence of the lattice structure, we performed and analyzed several results, including root stress, body stress, contact pressure, and total deformations. An analytical calculation for the contact pressure was conducted and 500.2 MPa was obtained, which was used to verify the results of the FEM analysis. The contact pressure is calculated based on equation (1):

$$\sigma_{H0} = Z_H Z_E Z_\varepsilon Z_\beta \sqrt{\frac{F_t}{bd_1}\frac{u+1}{u}} = 2.49 \cdot 189.8 \cdot 0.88 \cdot 1 \cdot \sqrt{\frac{2083}{20 \cdot 144}\frac{1+1}{1}} = 500.2\ MPa$$

The FEM analysis for the first case, involving a solid gear, provided a contact pressure of 498.69 MPa, resulting in error of -0.3% compared to the analytical calculation.

All the results from the FEM analysis are presented in Table 2, while Figures 4 to 8 show the outcomes for Case C, which involves a gear with a lattice structure body and 40% infill. As expected, there were no significant changes in contact pressure and root stress. However, substantial changes were observed in the stress within the gear body. For instance, the stress increased from 8,595 MPa for the solid gear, to 42,635 MPa for the gear with a lattice structure body and 60% infill, 136.45 MPa for 40% infill, and 514.24 MPa for 20% infill. Total deformation also showed variations, ranging from 0.013 mm for Case A, 0.0159 mm for Case B, 0.0175 for case C to 0.0245 mm for Case D.

Furthermore, the mass of the gears changed significantly, which is a big advantage for using lattice structures. While a solid gear weighs 2441.3 g, Case D exhibited a decrease to 1261.9 g, representing a 48.31% reduction. Figure 8 illustrates the comparison between mass reduction and stress increase in the gear body. As a result of the significant mass reduction, the body stress increased considerably. The results imply that in Case D, damage would likely occur in the gear body rather than in the root of the tooth or on the contact surface of the gears.

Table 2. FEM Analysis results.

	Root Stress [MPa]	Body Stress [MPa]	Contact Pressure [MPa]	Total Deformation [mm]	Gear Mass [g]
Case A	63.922	8.595	498.69	0.013	2441.3
Case B	70.454	42.635	486.25	0.0159	1839.5
Case C	70.188	136.45	480.87	0.0175	1570.33
Case D	71.689	514.24	481.71	0.0245	1261.9

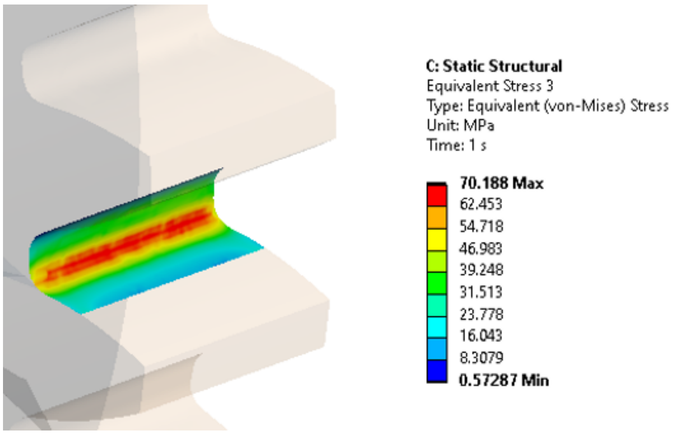

Fig. 4. Root stress (Case C)

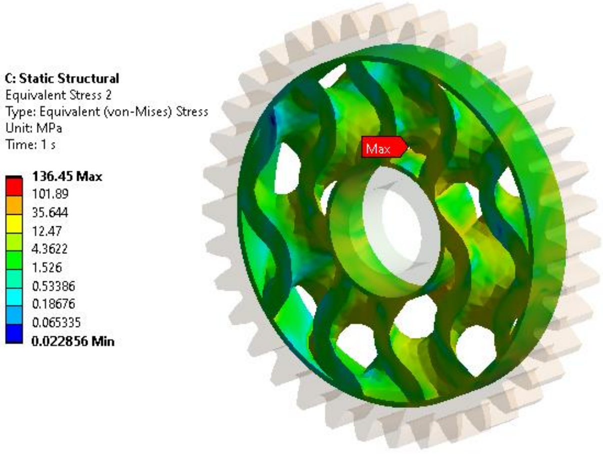

Fig. 5. Body stress (Case C)

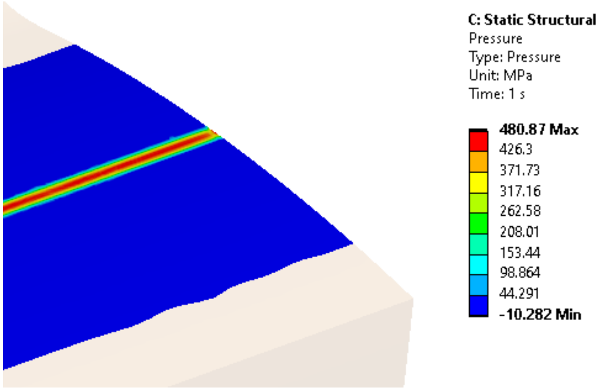

Fig. 6. Contact pressure (Case C)

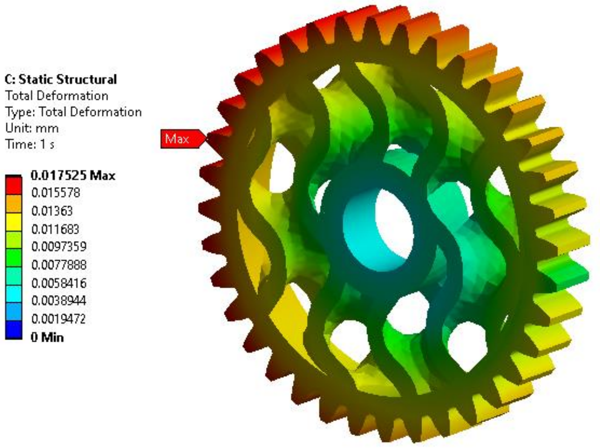

Fig. 7. Total deformation (Case C)

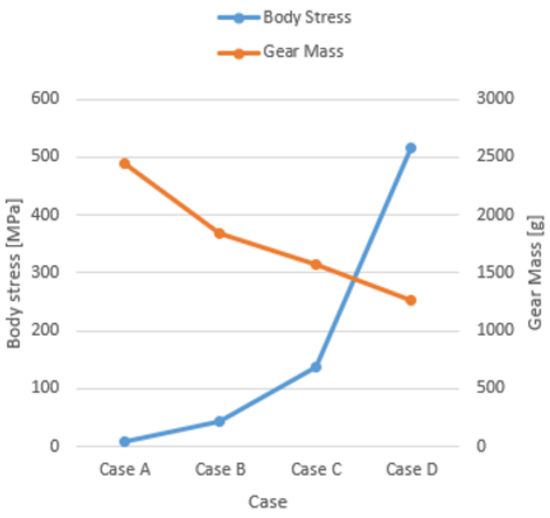

Fig. 8. Comparison between gear mass and body stress

6 Conclusion

Usage of lattice structures in gears offers significant advantages in terms of mass and vibration reduction. However, it is crucial to ensure that the load-carrying capacity of the gears is not compromised. In this study, various cases were analyzed, and the results indicate that reducing the infill percentage in the lattice structure significantly reduces the gear's mass. This reduction comes at the cost of a substantial increase in stress within the gear body, both root stress and contact pressure. Consequently, the gear body becomes more exposed to failure compared to the root of the teeth or contact surface.

As expected, the root stress remains relatively unaffected, as there were no changes in the rim's thickness during the analysis. Future research should investigate the influence of rim thickness on root stress, determining the minimum rim thickness required for gears with a lattice structure body. Such analysis would provide valuable insights for optimizing the design and performance of gears with lattice structures.

The use of lattice structures offers weight and vibration reduction. However, designers must carefully consider the trade-off between mass reduction and increased stress in the gear body. By addressing these concerns and conducting further research, gears with lattice structures can be designed to achieve optimal performance and durability.

This research was part of the project DfAM (Design for Additive Manufacturing), supported and financed by the Faculty of Mechanical Engineering – Skopje.

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