DESIGN OPTIMIZATION OF GEAR WHEEL BODIES IN ORDER TO REDUCE WEIGHT

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Design solutions for the shape of the gear bodies depend on several factors such as the size of the wheel, material, production method or use. Cast forged or welded gears are used for larger gear wheels. One of the requirements for gear shape solutions is weight reduction. Such an effort can be achieved by changing the dimensions of the given wheel, while maintaining the required stiffness of the gearing. The paper is devoted to the problem of optimizing the shape of gears in order to reduce the weight of the gears, but while maintaining the best possible stiffness of the teeth.

KEYWORDS

Optimization, gear body, weight, shape, topology simulation

1 INTRODUCTION

Gears are the most important element in the field of engineering. They are the basic structural element of gearboxes and so are part of most machinery and equipment, also an important element for the automotive and aerospace industries in particular. Spur and helical gears are the most common type of gear due to the simplicity of design and manufacture. At the same time, they are cost effective (price) and require less maintenance [Kuczaj 2023]. The design of gearbox for the required conditions is becoming a challenging task with the increasing interest as well as frequency of use of gears.

The gears are designed to be as light as possible while maintaining the requirements for durability and load capacity of the gears, while maintaining wear resistance and ensuring proper cooperation. For example, automotive transmissions today are designed to be as light as possible while reducing fuel consumption and thus CO_2 emissions [Czech 2022]. Of particular importance in the automotive and aerospace industries is the reduction of gear weight. When the ratio of the weight of the gearbox to the power transmitted is improved, the negative impact of the dynamic phenomena occurring during its operation is reduced applies here.

Dziubek et. al. authored a paper where they made an analysis for a few selected design shapes of gear wheel. The solutions were performed on spur gear resulting in various modifications of this gear. Each solution was compared with the solid baseline variant. The aim of the paper was to lower the weight of gear wheels used in automotive and aviation industry, where it was stated that the required strength parameters must stay unaffected by the mass reduction [Dziubek 2022].

One of the problems for gear design is the isoparametric discretization of point for tooth surface. This was addressed by Wu et. al. in their work where they derived advanced method based on geometry with the aim to gain points with even geometry distribution on the surfaces. These points were discretized according to gear blank followed by mapping of sample points and surface points. This was followed by algorithm to recalculate the surface points [Wu 2018].

Magerramova et. al. presented a work which was focused on additive technologies for the mass reduction of the gearbox by up to 15% while the mechanical properties stayed unchanged. in the work the mechanical and physical characteristics of aluminum alloys were analyzed as well, where the exact materials were established for the gear reducer. The proposed suggestion was analyzed by the finite element method for the synthesis of the aluminum alloy powder. this process resulted in the prototype of the gearbox housing manufactured by 3D printer [Magerramova 2022].

In the work of Wang et. al. the study of the gearbox housing for the vibrations was concluded. The study was performed in three major steps. The first step was to obtain the bearing dynamic loads by the dynamic equations. The second step was to obtain the vibrations of the gearbox by the means of finite element analysis. The third step was to specify the point of the highest-pressure level which was later taken as a design domain. The topology optimization of the gearbox body was done by using SIMP method with the rearrangement of the ribs according to the optimization. results showed high reduction of the noise levels [Wang 2015].

Weight optimization it is a challenging task where fewer solutions already exist. Such solutions contain an algorithms which are metaheuristic. Some of the methods used for optimizations are interior point method which is the most powerful algorithm used for nonlinear programming. Such algorithm was used by the Avcu et. al. In their work where they implemented numerical optimization algorithm with the aim of the mass optimization to reduce the weight [Avcu 2023].

Wei et. al. performed a study on a gearbox with the aim to reduce the overall weight. The conditions for successful optimization were to maintain the strength and rigidity. The study was performed by multiple load cases, static stiffness of the structure and first order natural frequency, where the objectives of the optimization were defined. The optimization was performed by simple method which in the later tests proved that the optimized gearbox had 7.8% less weight where the mechanical properties stayed unchanged [Wei 2012].

Manufacturing processes have a significant impact on the physical properties and final geometry of the manufactured part. Some of the influences on these properties are heat treatment. Experiment studying this area was done by Kagathara et. al. where they performed research on the weight reduced counter gear. The experiments showed that case hardening had a significant influence on the geometry of the gear wheel but also stated that it was impossible to understand such distortions just by the experiments. Therefore, they performed simulation of such manufacturing process where they discussed the similarities between simulation and experiments [Kagathara 2021].

In the paper of Lübben et. al. the problem of the distortion after the final heat treatment on the manufactured part was analyzed. The problem was illustrated by the various geometric modifications where the mass of the examined part was reduced up to the 43.6%. The geometry modifications of the gear in this paper are only used for the variations of the distortions and their distribution. Variations of incorrect functional behavior for gear were accepted, as the design was only aimed and the consequences of the final heat treatment. After the first analysis the influences of variations regarding the quenching process, the carbon profile and hardenability where presented for the variant with the lightest geometry [Lübben 2020].

The paper is devoted to the problem of optimizing the shape of gears in order to reduce the weight of the gears, but while maintaining the best possible stiffness of the teeth, which is an important factor affecting the noise and vibrations of the gearing.

2 DESIGN SOLUTIONS OF THE SHAPES OF GEAR WHEELS

Design solutions for the shape of the gears bodies depend on several factors such as the size of the wheel, material, production method or use. Cast, forged or welded gears are used for larger gear wheels.

Gear wheels of smaller dimensions can advantageously be made welded. The wheels are disc-shaped. The extension of the hub is achieved by welding the ring to the wheel, or by sliding the tubular hub into the hole of the wheel (Fig. 1).

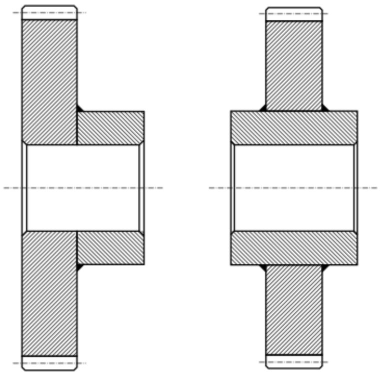


Figure 1. Welded gear wheels

Larger welded gear wheels have flat steel rims. The rim is connected to the hub, for example, by means of a plate with a circular shape, reinforced with ribs (Fig. 2) or without ribs (Fig.3).

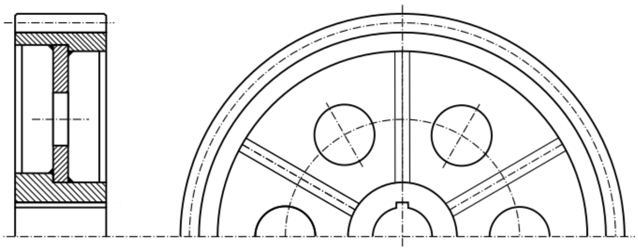


Figure 2. Welded gear wheel with plate and ribs

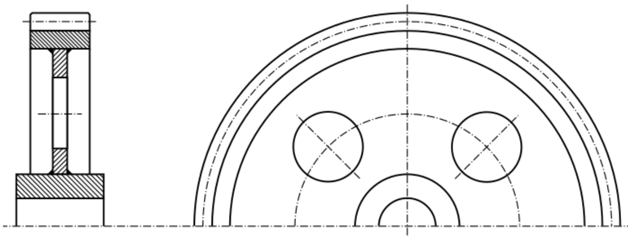


Figure 3. Welded gear wheel without ribs

The advantage of welded gear wheels is the reduction of weight, the production of a cargo model is eliminated, the production time is shortened and the price of the product is reduced. Welding is economically applied to a smaller number of products. However, the final processing must be done after complete welding.

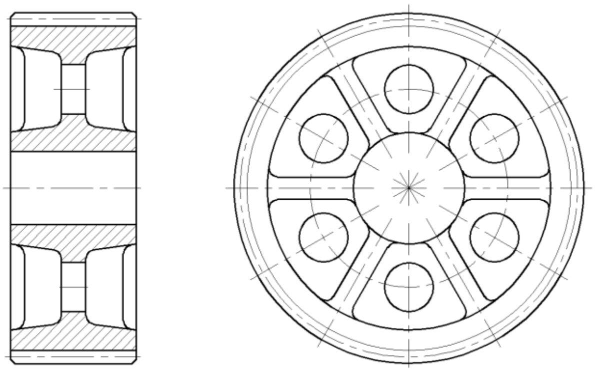


Figure 4. Cast gear wheel with web and ribs

Casting is mostly used to create gear blanks. However, by casting, it is also possible to create gearing without subsequent processing. The casting processes used for the production of cast gear wheels are sand casting, investment casting - suitable for creating gears from very hard materials that cannot be machined and shell casting - creates a smooth surface, reduces the number of necessary machining [Krenicky 2022]. The type of material used depends on the circumferential speed of the gear wheel. Cast gears of larger sizes have elliptical, cross or T-profile arms. They can be made with one (fig. 4) or two webs (fig. 5). The disadvantage of cast gears is that they carry less load than forged gears.

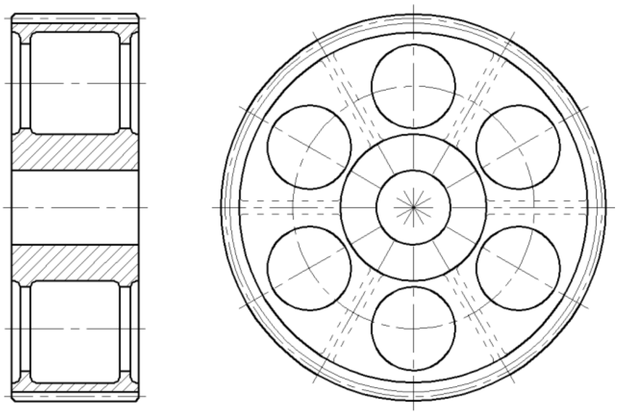


Figure 5. Cast gear with two webs

Forging is mainly used for the production of a semi-finished product for gears, which will later be machined into its final form. These blanks are formed by operations such as free forging or die forging [Moravec 2021]. The materials used for the production of forged gears can be ferrous and non-ferrous metals such as carbon steel, alloy steel, stainless steel, titanium, nickel, aluminum alloys and the like [Juzek 2017]. The most frequently used shape of forged gear wheel is shown in Fig. 6.

The solutions for large gears are influenced by the demands placed on them. One of such requirements is the design of a gear wheel with sufficient gearing stiffness and with the smallest possible body volume. Such a reduction in volume while maintaining stiffness means that the given solution consists mainly of changing the geometry of the wheel body.

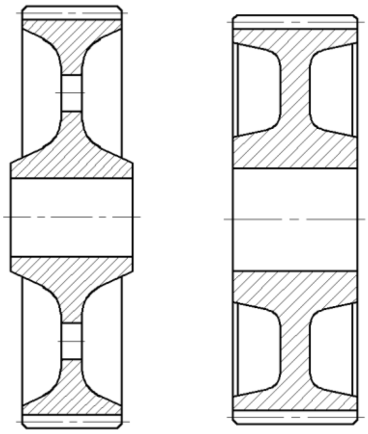


Figure 6. Forged gear wheels

Optimization also has its place in the structural design of structures. The methods of individual optimization procedures are used in the development or actual innovation of the gear mechanism. These operations are carried out for the purpose of lightening the gear mechanism resulting in reduced costs.

3 GENRATIVE DESIGN

The development of generative design started already in the 1980s, where most of the publications and information were only on a theoretical level without any concrete application in any industry. The first industry in which generative design started to be used was architecture. This sparked off interest from academics who also started to develop this kind of design, as there was potential in the combination of computing and evolutionary methods for previously non-standard and high quality outputs. In the field of design [Vajna 2005] developed an auto genetic theory of design by exploring the similarities between the design process in the context of design creation and the natural process of evolution (Fig. 7).

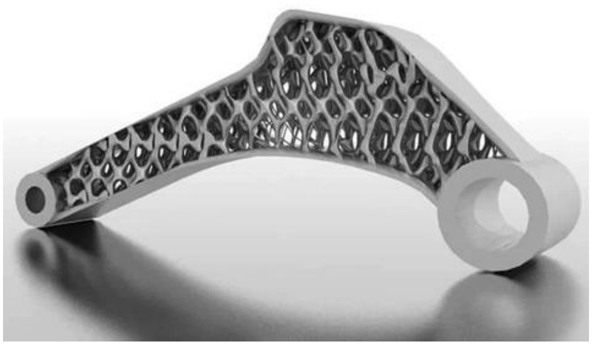


Figure 7. The result of generative design

According to evolutionary theory, the process of method progression can be described as a continuous improvement of the baseline solution controlled by initial conditions, boundary conditions, and constraints. These factors influence the design process and open new spaces for it. Due to the variety of applications, generative design currently has no universally accepted concept. According to [Krish 2011], "generative design" is a design-driven, parametrically constrained design exploration process that uses parametric CAD tools designed to support design as an emergent process. However, there are now applications used in design that go beyond the use of standard CAD tools and are not constrained by parametric models [Kazi 2017].

Using a process also known as generative design, which involves some automation and process autonomy, several designs are created. The design process mimics the evolutionary process in nature by starting with one or more different designs and changing them over time into solutions that are more suitable for requirements constrained by specific conditions. Solutions of Design Criteria that are not satisfied or constraints that are not suitable are discarded and the search (evolution) process moves in a different/new direction.

The term "generative design" is often used to refer to computer-aided design, despite the fact that it can also be done with pen, paper and a set of rules. The results produced can take a variety of formats, including images, models, sounds and animations.

4 TOPOLOGY SIMULATION

The method, called topological optimization, aims to maximize the distribution of material in given selected space, taking into account load and boundary conditions. It is often used at the initial design stage to study and assess different design options in accordance with predetermined criteria such as weight reduction, stiffness increase, stress reduction and strain reduction, among others.

Topology optimization programs are designed to simplify the work of users who are working with iterative design processes and multivariate analyses. They also encourage creativity, offering often overlooked solutions. Along with shape and dimensional optimization, topology optimization is one of the three basic subcategories of design optimization. While shape optimization needs to ensure design criteria and objectives (e.g., reducing stress concentration or extending fatigue life), contour optimization considers specific contour characteristics determined by the location of nodes (Fig. 8).

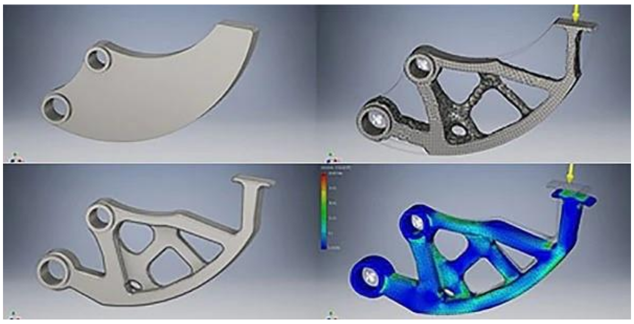


Figure 8. Procedure and result of topological optimization

In order to obtain the best solution in terms of mass, stress, strain and other factors, the values of the design parameters related to the cross-sectional areas of the elements are adjusted during dimensional optimization. This is often used when solving problems with load-bearing bars, building frames and beam structures. These methods, unlike topological optimization, only allow for changing the values of their parameters, not adding or removing new elements or voids in the element structure [Tejani 2017]. Unlike topological optimization, which simply needs a specified initial volume, shape and dimensional optimization approaches need an initial parametric model to enable optimization.

5 APPLICATION IN THE DESIGN OF SPUR GEAR BODY SHAPES

The 3D modelling capabilities and powerful design automation tools built into SolidWorks were used to digitize the model. The designer must take into account that the optimized model cannot be divided into multiple solids as one and must be uniform. This is a critical requirement because the SolidWorks topology optimization module does not support simultaneous optimization of multiple parts/bodies or assemblies. Although it must be taken into account that some elements must be unchanged in terms of geometry (holes, feature profiles...). In this case, the model must have boundaries defining this area.

External loads and penetrations are defined in the same way as in finite element simulation. The only difference is that force loads are placed on each tooth of the gearing to ensure a "patterned" (repeated) shape of the optimized gear, meaning that there will be no sections with less or no support (Fig.9).

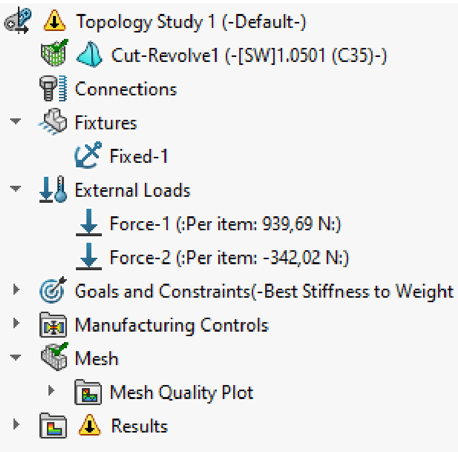


Figure 9. Defined loads and constraints

Then, it is necessary to determine the optimization objectives and criteria for topological optimization. For a given material reduction condition, the goal of topological optimization will be to reduce the volume of the body to the target criterion, but at the same time to ensure that the resulting geometry achieves the highest body stiffness.

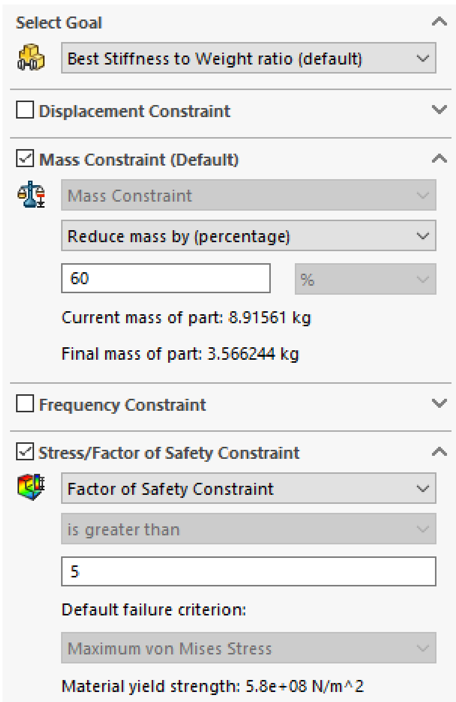


Figure 10. Defined optimization objectives

The definition of the objective and criteria will affect the material reduction. The geometry of the solution with the highest stiffness is determined by the material loss and the final shape of the optimized solid, in such a way that volumes are removed from the "full" solid (Fig.10). The constraints define upper and lower criteria for the largest displacement that can be displayed in the 3D model or specify constraints on the fraction of mass that can be removed.

In the topology optimization process, the material is distributed in a way that the optimization objective is met for the given geometric criteria. However, the use of conventional manufacturing processes such as casting or forging can cause problems in the creation of the 3D model. Applying appropriate manufacturing control criteria to the optimization model can prevent undercuts and hollow pieces. The manufacturing controls criteria ensure that the optimized 3D model can, for example, be correctly molded or removed from the mold. Four different types of manufacturing controls are available in the SolidWorks simulation:

- Thickness control. Specifies a criterion to optimize the model topology to avoid creating parts with hard-to-make walls that are too thin, or parts that are too thick.
- Preserved region. This criterion adds preserved parts (surfaces) to the 3D model that do not change after the topology optimization time, thus preserving the geometry of these surfaces, which are crucial for the functionality of the model (Fig. 11).
- Symmetry plane. The optimized 3D model is symmetric with respect to one or more predetermined planes using the symmetry criterion. Depending on the layout of the design, a planar symmetry can be chosen that is either half, quarter or eighth.
- De-mold direction. This function simulates the extraction of the optimal 3D model from the mold.

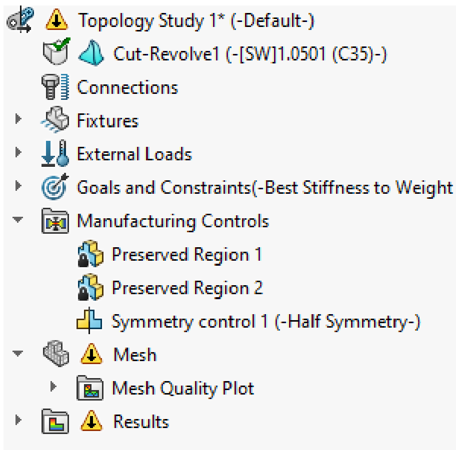


Figure 11. Defined manufacturing controls

After defining the optimization criteria and selecting the boundary conditions, the optimization itself follows. The process is automatic, controlled by algorithms, but it is advisable to set the number of iterations to be performed before it starts. The iterations serve as sub-simulations of the adjusted volumes, with each successive iteration aiming to produce a more optimized shape than the previous one. Naturally the more iterations are chosen the better the results but this is at the expense of time where the optimization time increases. The result of the optimization is in the form of a color-coded model (similar to FEM) where the colors divide the volumes from "excess" to "suitable to keep" to "necessary to keep" (Fig. 12).

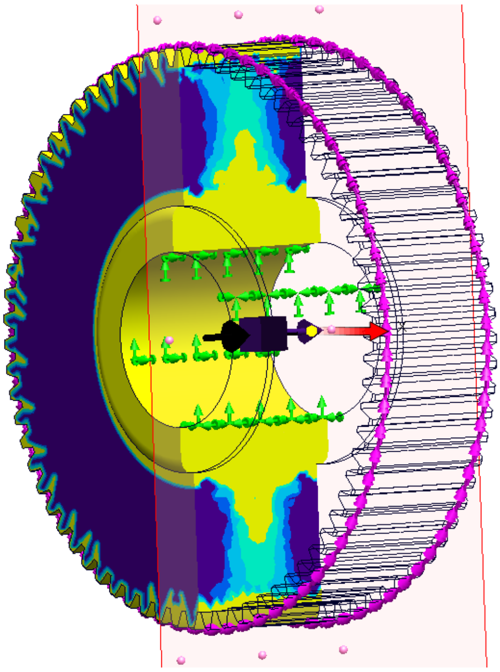


Figure 12. Results of topology optimization

The resulting models are exported to either volume or area formats. However, these need to be edited "smoothed out" as the results are related to the geometry created by the finite element mesh (Fig.13).

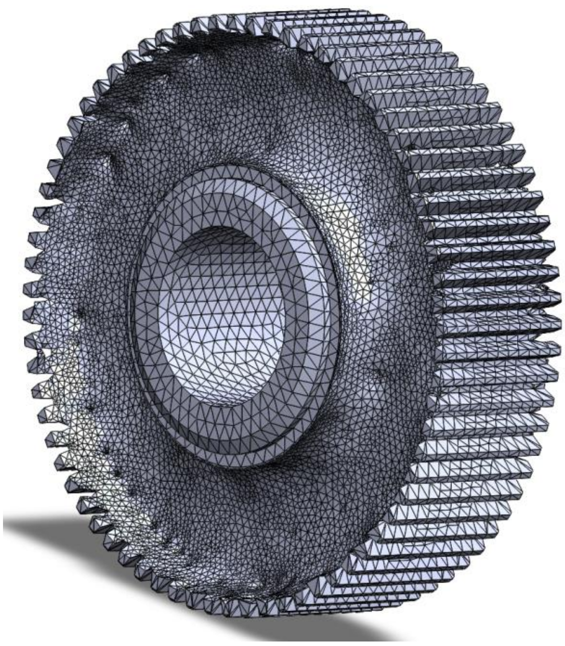


Figure 13. Exported model

The aim was to design a gear with the lowest possible weight, where the next parameter considered was the stiffness of the gearing. The gearing stiffness is significantly affected by the thickness of the rim under the gearing, and this was set to a constant value for all the newly developed variants. The modified wheel web shapes looked as follows after modification (Fig. 14).

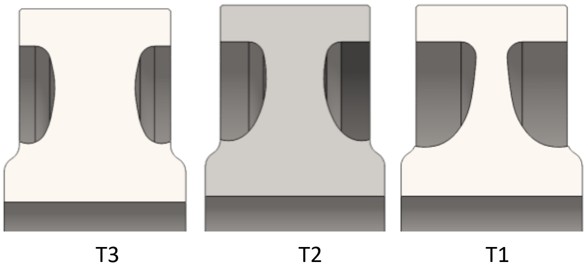
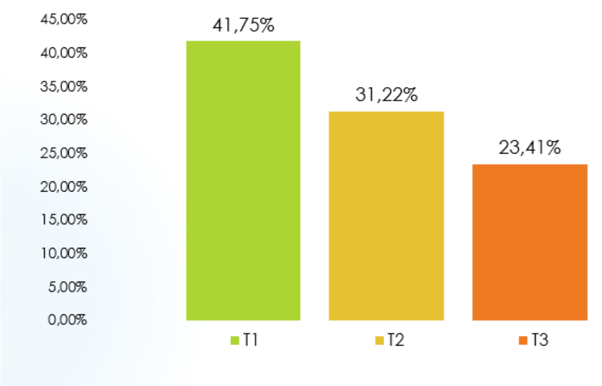


Figure 14. Resulted web shapes

The optimized 3D model can be exported as a solid model, solid or graphical solid. If the model will be created on a 3D printer without additional design modifications, the suitable alternatives are "Surface body" and "Solid body". When the "Graphic solid" option is selected, the optimal design is exported in a boundary geometry representation format that is more suitable for editing and post-editing. In the first 3D model, SolidWorks allows the insertion of the exported graphic solid. After overlaying the two 3D models, the first step is to determine their differences. The simplest procedure to achieve this is to make the optimized model opaque and adjust the transparency of the original model to semi-transparent.

SolidWorks can have a problem with surfaces whose shape needs to be preserved. The hub, which provides the connection between the wheel and the shaft, and the gearing, with a certain thickness of the rim underneath to maintain the stiffness of the gearing, are the preserved surfaces (areas) for topology optimization. The fact that the thickness of the rim was set to a constant value and thus not optimized is another deficiency of the aforementioned procedure. The following procedures will also incorporate and address these shortcomings.



A comparison of the weight loss for the wheel shapes of Figure 14 versus the full gear body shape is shown in Figure 15.

Other optimization shapes for the 71-tooth, 2.5 mm module spur gear were also investigated and are shown in Table 1. In this case, the stiffness of the gearing is replaced by examining the deformation of the gearing at the point of greatest tooth tension. The principle applies that the lower the stiffness, the greater the stiffness of the teeth. Deformation of the teeth is solved by the finite element method.

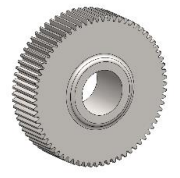
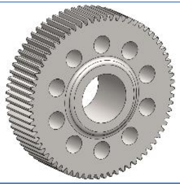
Image of the model with label	Total weight [kg]	Weight loss [%]	Deformation of the gearing in the middle of the width [mm]	
			Above the relieve element	Above the material
 Model 1	8.929	-	-	0.00935
 Model 2	7.704	13.72	0.00986	0.00947
 Model 3	6.790	23.96	0.01085	0.01002
 Model 4	4.719	47.15	0.01079	0.00962
 Model 5	4.445	50.22	0.01157	0.01068

Table 1. **Gear body optimization results for each variant**

The best weight reduction resulted from the suggested models/variants 4 and 5. However, out of all the suggested models, version 5 yielded the poorest deformation outcomes. Variant 4 had good results for gearing deformation as well as weight reduction that was compared to the best variant. Models 2 and 3 showed insufficient weight reductions while having relatively modest deformation results (compared to the lowest value). Given the weight loss Percentages and deformation values, model 4 would result in the best-performing optimization when these considerations are taken into account. This publication will form the basis for further optimizations, analyses, and software generation of body geometries in further studies.

6 CONCLUSIONS

The engineering industry is one of the most important sectors in our national economy. It forms an integral part of our economy and determines the direction of progress in the production of engineering products, including gears. They are the basic structural element of gearboxes and thus are part of most machines and equipment. Their production is considered one of the most demanding in the entire engineering industry, primarily due to their complexity and high requirements for the accuracy and efficiency of the entire production process.

Optimization also has its place in the structural design of structures. The methods of individual optimization procedures are used in the development or innovation of the transmission mechanism itself. These operations are carried out in order to relieve the transmission mechanism itself, which results in reduced costs.

Large gear wheel solutions are influenced by the requirements applied to them. One such requirement is the design of a gear with sufficient gearing stiffness and with the smallest possible body volume. Such a reduction in volume while maintaining stiffness means that the solution in question consists mainly of a change in the geometry of the wheel body.

The practical example was the comparison of the deformation values for each variant in the first step compared with the solid body variant results. Later the variants were compared with each other for the purpose of finding the best-proposed shape. The relief hole variants functioned almost as well as the solid body variant for the values of the material analysed above. Variants 3 and 5 had the lowest results, with version 5 having the greatest deformation value.

The best variant, according to the data above, was variant no. 2, and the poorest variant was number 5. The results for the remaining two variations, which fell between variants 2 and 5, were nearly identical.

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