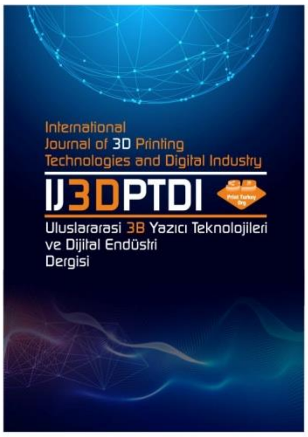

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OPTIMIZATION OF MODELS OF MACHINE PARTS FOR 3D PRINTING

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ABSTRACT

When manufacturing machine parts using additive 3D technologies, we are faced with the task of choosing a specific manufacturing technology, material, and settings for 3D printing. These factors affect the manufacturing time, cost, accuracy, strength and other performance criteria of machine parts. The purpose of the study is thus to develop recommendations for optimizing models of machine parts for 3D printing. The study describes the main approaches to optimizing three-dimensional models of machine parts at the design stage. This optimization allows to avoid a number of problems that arise when using various 3D technologies: FDM (fused deposition modeling), SLA (laser stereolithography), etc. Depending on the type of the designed part and the applied additive 3D technology, additional requirements and restrictions are imposed on the models. The issues of optimizing models in terms of 3D printing time, manufacturing cost, geometry (accuracy) of the resulting model are considered, and the issues of the strength of the entire part or its individual elements are also partially investigated. Specific design solutions and recommendations for manufacturing rotation parts, in particular, shafts and gears, are given. The issues of occurrence of some defects associated with overheating, uneven cooling and plastic shrinkage are considered. The simplest models for studying strength of critical parts are described. Recommendations for determining the properties of machine parts manufactured using additive 3D technologies are developed. This study will be of interest primarily to the developers of 3D models and is aimed at eliminating some of the problems that arise during 3D printing at the product design stage.

Keywords: 3D Technologies, Machine Parts, Strength, Accuracy, Models, Optimization.

1. INTRODUCTION

Nowadays, there are many additive technologies that make it possible to obtain a prototype of a designed product (and in some cases, a working machine element) in a relatively short time. Among the variety of additive technologies (Fused deposition modeling, Stereolithography, Selective laser sintering, Laminated object manufacturing, Multi-jet modeling, PolyJet, 3DP, Liquid interface production, Direct metal deposition and others) [1], some are available to a wide range of users due to their simplicity and relative cheapness. Among such available technologies are Fused deposition modeling (FDM) and Stereolithography (STL or SLA), so we will pay the most attention to them.

These technologies make it possible to obtain products with sufficient detail and mechanical strength to be used as final products. When using FDM and SLA technologies [1–7], with the right choice of raw materials, it is possible to obtain imprints similar in mechanical characteristics. Other considerations for the choice of printing technology and raw materials are the accuracy of the resulting print and the speed of its production. Compared to FDM technology, SLA printers in the same price range offer greater print accuracy. The main accuracy parameters of the 3D printers used for the current study are given in Table. 1.

Table 1. Accuracy of selected 3D printers.

Additive technology	**FDM**	**SLA**
Print area dimensions, mm	300*300*400	192*120*250
Layer height: ΔZ , μm	100 200 300 500	35–51
Approximate error along XY-axes, μm	±10	±5
Approximate accuracy along Z-axis, μm	$\Delta Z \pm 5$	$\Delta Z \pm 2$

Thus, the standard value of the layer thickness along the Z-axis (vertical axis) for SLA can be 10-35 μm, for FDM - 100-500 μm. Printing accuracy in the XY plane of SLA printers is also higher than that of FDM.

The next equally important parameter of detail reproduction is the speed of its printing. In view of the fundamental difference between technologies, it is rather problematic to make an unambiguous conclusion about the printing speed, since it depends on many factors: raw materials (for SLA it affects the polymerization rate), the area of printed layers (for FDM, the length of the molten substance to be laid), etc.

The cost of manufacturing parts using 3D printing depends also on many factors, first of all, on the choice of the printing technology itself. For the FDM and SLA technologies considered here, the price depends not only on the accuracy and dimensions of the model, but also on the possibility of using high-temperature materials.

With the advent of new, in particular additive technologies, there is a need to revise the principles of design: so that some parts can be obtained by 3D printing methods, some using copying by casting on a printed master model, while others must be obtained by classical methods. Attempts to use additive technologies to reproduce parts designed and manufactured according to classical approaches (from a workpiece through further machining) often fail to produce a workable part. In other words, it is necessary to take into account the peculiarities of creating 3D models for 3D printing, as well as to pay attention to their optimization based on the type of the part and the printing technology. Manufacturing parts for various purposes can be a difficult task already at the stage of choosing technologies and raw materials, often solved by trial and error.

We mention several works, which results were used in the present study.

A comprehensive review of the mechanical properties of polyjet printed and FDM printed parts is found in [6]. Here the influence of process parameters such as built orientation, built mode, finish type, part spacing and layer thickness on the mechanical properties are also discussed. The mechanical properties of important and potential polymeric materials are reviewed.

The authors of [7] try to establish a set of rules to be followed in FDM 3D printing process using ABS (Acrilonitril-Butadien-Styren) type plastic materials. This article refers also to printing constraints generated by the machine work load limitations and the extruded material.

In [8], it is indicated that 3D printing has huge potential, however, this technique requires further improvement and further investigation due to the shortcomings such as poor surface finish and low mechanical strength. In this work, the determination of the best orientation for printing a model with different mechanical properties, namely tensile strength, impact strength and hardness, is carried out. Experiments were conducted to investigate the mechanical properties. ABS samples were printed out according to the ASTM D638, ASTM D785, and ASTM D256 standard for each mechanical property.

We highlight article [9], where the different infill patterns and volume related percentages are compared by using the FDM technology. Non-standardized bending test were carried out with two loading orientations. The results indicate clearly the relation between the mass of the product and the manufacturing time, the pattern and percentage, as well as the decrease of the resilience in products with hollows.

In [10], a process of producing new polymer matrix composites with nanosized barium ferrite (BaFe12O19) as ferromagnetic filler, acryl butadiene styrene (ABS) as polymer matrix and an extrusion-based method, namely fused filament fabrication (FFF), as 3D printing method is described comprehensively. The whole process consists of the individual steps, namely, material compounding, rheological testing, filament extrusion, 3D-printing via FFF and finally a widespread characterization of sample regarding its appearance, mechanical properties such as tensile and bending behavior as well as the aspired magnetic properties. In addition, an extensive discussion of typical printing defects and their consequences on the device properties is undertaken.

In [11], the influence of different parameters of the Fused Deposition Modelling process with continuous carbon fiber reinforcement upon tensile strength of manufactured parts is analyzed. To this end, the appropriate behavior of samples designed according to ISO 527 standard is verified in a preliminary test. The result of the study is that the tensile response of a printed part can be predicted in advance as a function of the chosen manufacturing parameters.

The main insufficiency of prototypes made by 3D printing with FDM method is structure inhomogeneity resulting from the basic principle of this technique. In [12], it is shown, how the structure of the FDM prototypes is affected by changing the processing temperature and location on the base plate. In order to define the influence of the processing temperatures on the structure of FDM prototypes, various head and envelope temperatures are applied for printing the samples. The samples are analyzed by means of computed tomography to determine changes in layers structure, dimensions and the portion of unfilled volume in sample. The obtained results show inhomogeneous distribution of material in the whole volume of scanned samples. It has been found out that structure homogeneity represented by the volume of non-filled area is affected even by the shape of fabricated part.
In [13], the tensile strength of parts built using FDM process is measured. ABS and ABS plus parts were built with different building parameters and were tested according to the ASTM D638-02a standard on a tensile test machine. The building direction was found to have no significant influence on the tensile strength of the parts, although the parts were as expected anisotropic. Parts built with larger layer thickness have shown lower tensile strength. The average deviation between the nominal and the experimental tensile strength was about 15% for the ABS and about 42% for the ABS plus material. The ABS plus showed on average 9% higher strength than ABS.

Work [14] presents a metamaterial design paradigm using gears with encoded stiffness gradients as the constituent elements and organizing gear clusters for versatile functionalities. The design enables continuously tunable elastic properties while preserving stability and robust maneuvrability, even under a heavy load. Such gear-based metamaterials enable excellent properties such as continuous modulation of Young's modulus by two orders of magnitude, shape morphing between ultrasoft and solid states, and fast response. This allows for metamaterial customization and brings fully programmable materials.

In [15], three-dimensional (3D) printing of synthesized mechanism with the aid of FDM technique is demonstrated. The mechanism taken into consideration is eight link gear variable topology mechanism having two degrees of freedom. The general synthesized mechanism is proposed and several parameters for mechanism printing are taken into account. Various 3D printing techniques are available and the focus of the paper is on the FDM, which constitutes a part of additive manufacturing. This process creates an insight into the practical observation of mechanism behavior before proceeding to fabrication.

The objective of work [16] is to use advanced manufacturing process i.e. Direct Metal Laser Sintering (DMLS) to produce complex design component such as spur gear. 3D modeling of the spur gear has been done using Solidworks software by considering the design parameters of the spur gear. Finite Element analysis software ANSYS has been used to study the equivalent von Mises stress and the total deformation developed in the spur gear for the given torque. In this study spur gear has been manufactured using DMLS by using maraging steel powder. The optimized process parameters have been used to manufacture the spur gear and these types of gears can be used in any power transmission system.

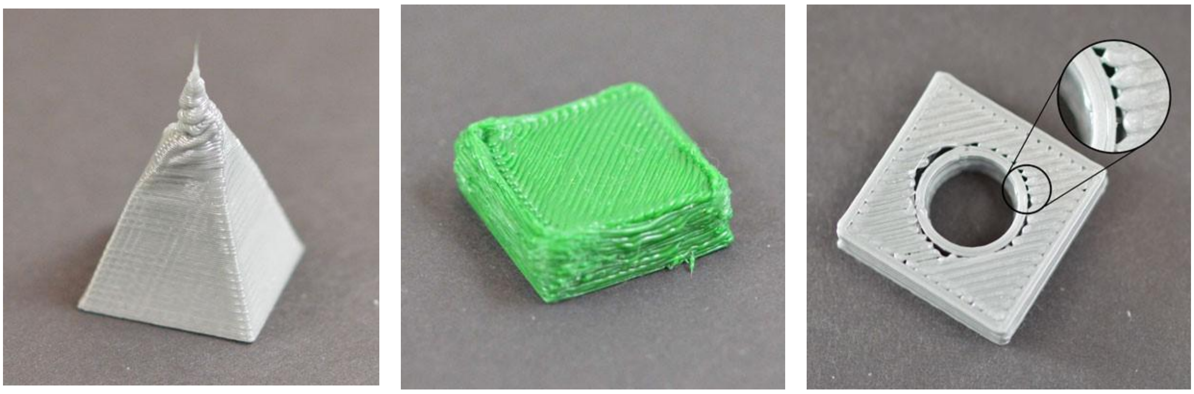
Most of the research is devoted to a deep study of specific topical issues, but is not focused on changes in the formulation of problems for designers using additive technologies.

To obtain workable machine elements, not only the appropriate printing technology should be chosen but also the geometry of the element should be adapted to the specific manufacturing technology. This work is devoted to this question. The material of this study will be of interest, first of all, to designers and is intended to eliminate some of the problems that arise during 3D printing at the design stage.

2. MATERIAL AND METHOD

Since the printing technologies under consideration are rather "clean", a design engineer is often both a technologist and a manufacturer of the designed part, which in turn significantly reduces the time for obtaining the finished product. Many descriptions of the process and subtleties of printing using additive technologies have been published, however, choosing the optimal process parameters is not an easy task. With the wrong choice of material or parameters, there may be discrepancies in shapes and sizes [3] (Figure 1).

Note that when 3D printing gears, which are rather complex objects, the number of possible defects only increases, as shown in Figure 2.



(a) (b) (c)

Figure 1. Common 3D printing defects [3].

(a) (b) (c)

Figure 2. Defects in 3D printed gears.

Depending on the purpose and the design stage of the product, the following factors may be decisive.

In the case of receiving the first layout to assess the actual size, ergonomics, etc., there is a need for the fastest possible print. Unfortunately, the printing process is quite lengthy and, depending on the model, can last tens of hours. Most people who first encounter 3D printing are "unpleasantly" surprised at the speed of printing. The desire to speed up the printing process is but natural. To this end the following ways are used:

- ❖ increase in the layer thickness;
- ❖ adding internal cavities;
- ❖ decrease in density / departure from continuity.

The first and easiest way to speed up the printing process is to increase the layer thickness (Figure 3), which entails a deterioration in geometry, with almost unchanged strength (sometimes even a slight increase can be observed, depending on interlayer adhesion).

Figure 1. Common 3D printing defects [3].

Figure 3 is taken directly from the website [4] (https://3dmanufacture.com.ua/) of a company offering 3D printing services on a commercial basis in fairly large volumes. It very clearly shows the surface cleanliness in FDM 3D printing. Note that well-visible discrete transitions are quite suitable for non-working surfaces. However, in some cases, the working surfaces are not smooth enough.

Sometimes a non-smooth surface can be used in a positive way, for example, for applying and holding greases on work surfaces or decorative coatings. Only an experienced designer can correctly take this circumstance into account.

The second way is a decrease in density (avoidance of continuity), in particular, the addition of internal cavities. In this way, it is possible to preserve the outer geometry and ensure the required surface quality. In turn, the lack of continuity leads to a noticeable deterioration in strength. When obtaining a rough copy to evaluate geometry and ergonomics, the reduction in strength is often not so significant.

In the third way, so that the loss of strength is not critical, it is necessary to lighten the section even at the stage of creating three-dimensional models based on appropriate calculations, while programs for preparing the executable firmware ("slicers") cannot be trusted to perform this action automatically.

The main approach to maintaining the minimum required strength of parts is to maintain the minimum thickness of surfaces (at least 1 mm for small parts), using optimal fillings and internal structure. Among the rational types of infill patterns, the following are offered:

- ❖ classical square grid;
- ❖ cellular (hexagonal);
- ❖ gyroid structures;
- ❖ triangular flat;
- ❖ tetrahedral spatial structure;
- ❖ radial-arc structure (for bodies of revolution).

We note that work [9] presented in the analytical review is devoted to a detailed study of different infill patterns.

3. RESULTS

3.1. Features of 3D printing of rotation parts / shafts

It has been experimentally established that in order to print elements of rotation, the geometric axis of symmetry of the model must be located vertically.

Studies have shown that it is practically impossible to print shafts immediately with nominal dimensions (without allowances). When trying to immediately print a real shaft design, there are always problems with the deviation of the geometric shape and its dimensions (and even defects) in the initial section (Figure 4). Therefore, it is necessary to provide additional cylindrical sections in the design of the part, which are printed first. For subsequent machining of surfaces of rotating parts on a lathe, these cylindrical sections will help to avoid distortion of the following sections of the part, to increase the rigidity of fixing the part in a 3-jaw chuck and to provide the necessary centering accuracy. After turning machining, these additional sections are cut off. Note that the use of additional massive initial sections also makes it possible to avoid the well-known problem of workpiece tear-off during printing (Figure 5).

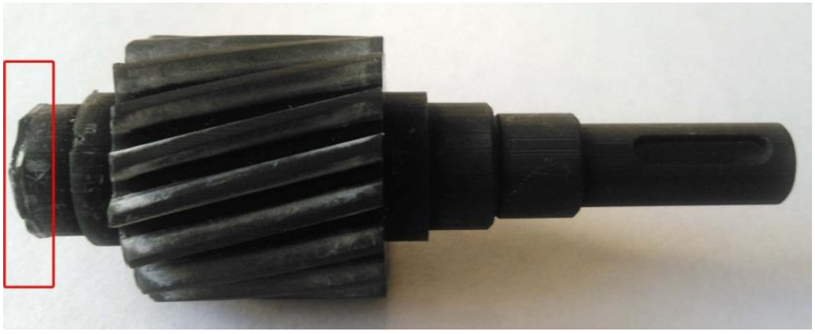


Figure 4. Printed pinion shaft.

Figure 5. Breakaway workpiece.

3.2. Features of 3D printing of gears

To ensure high-quality printing of gears, when creating or preparing a 3D model for printing, additional overflows or supports for teeth and protrusions must be provided. As a rule, modern "slicers" offer the creation of additional reinforcements / props on non-working surfaces (Figure 6) in automatic mode.

However, this problem can be solved even at the design stage by a slight change in structural forms. So the design provides for special expansions and slopes, which are then removed by subsequent machining (for example, on a lathe).

Studies have shown that a high-quality gear wheel can be obtained without additional supports by optimizing the model, namely by introducing an additional taper. It is found that the angle depends on the selected technology (FDM and SLA), material selection and print mode. For SLA technology an acceptable print quality of the model can be achieved already at an elevation angle of 15 degrees (see Figure 7).

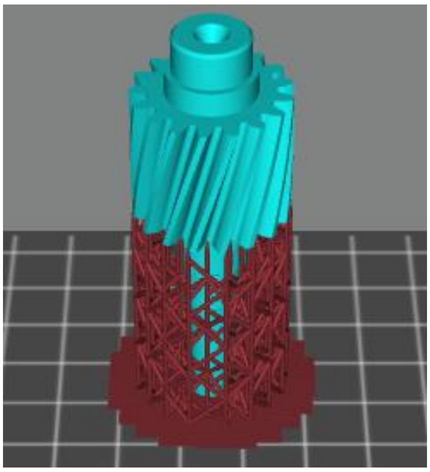
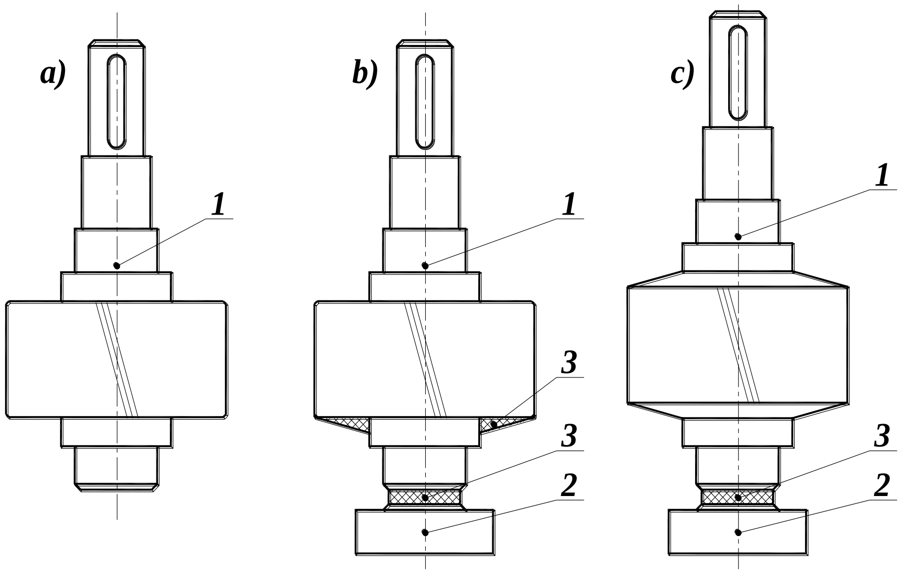


Figure 6. Support structures for 3D printed gears.

Figure 7 (a) shows a non-optimized model of a gear shaft. Figure 7 (b) shows a model optimized for 3D printing with further machining on a lathe (with one slope). Figure 7 (c) shows an optimized model with two slopes to increase the rigidity of the gear.



(a) (b) (c)

Figure 7. Design features of 3D printing pinion shafts:
(a) – base model; (b) – optimized model I; (c) – optimized model II.
1) base element;
2) an additional cylindrical section for subsequent machining of the surfaces of rotation parts on a lathe; 3) the area to be mechanically removed by machining (cut area)

3.3. Body parts

In order to successfully obtain a 3D printed sample of specific body parts, it is desirable to introduce a number of additional requirements and restrictions, similar to those introduced during casting, even at the design stage, such as the requirements for minimum wall thickness, introduction of additional slopes, laps and minimum curvature radii, where necessary.

3.4. Assemblies

When creating complex assembly structures (assemblies), which consist of a large number of elements, one should not strive to produce all parts and assemblies using 3D printing. On the contrary, ready-made standard products should be used as much as possible. As particularly striking examples of such standard elements, we can list the following: oil seals, cuffs, rolling and plain bearings, retaining rings, screws, bolts, nuts, washers, studs, cotter pins, rivets, etc.

When creating prototypes, it is also advisable to manufacture geometric models of a very simple shape (for example, feather keys and cylindrical bushings) using other technological methods, which can significantly reduce their cost and increase reliability, strength, heat resistance, hardness, wear resistance and other performance criteria.

With 3D printing, it is also not necessary to try to get the finished product with nominal dimensions.

Printing accuracy depends on several factors: layer thickness of 100-300 microns (user choice), printer positioning accuracy and material shrinkage (depends on the specific product and plastic shrinkage). Depending on the size and shape of a particular product, the coefficients of volume / linear expansion, there is a change in size during cooling or final polymerization, most often shrinkage of the material occurs.

The designer needs to be guided by the basic concepts of mechanical engineering technology (tolerances, fits, dimensional chains). For many parts, only certain “working” surfaces are of importance, the correct characteristics of which can be achieved by applying the appropriate printing technology. Critical parameters of working surfaces, such as size, accuracy and roughness, can be achieved by subsequent machining, with providing the necessary allowances for grinding / polishing in advance. At the same time, the "non-working" surfaces (for example, side faces) can be left without additional processing.

3.5. Some issues related to the durability of printed products

Also the strength of the printed products depends directly on their filling and material. The mechanical properties of the material for 3D printing and the printed element itself should not be confused.

In modern literature, it is now not difficult to find the properties of materials for FDM printing, for example, in [5] the following Table 2 is given.

We highlight the official page [2] of the American company formlabs.com, the flagship of SLA technology. The website of this company has a very detailed guide to modern materials used for SLA 3D printing (https://formlabs-media.formlabs.com/ datasheets/1901266-TDS-ENUS-0.pdf). Numerous studies (including ours) have shown that the strength of parts can differ significantly in orthogonal directions. This is especially true for FDM technology.

Table 2. Material properties for FDM printing [5].

Title	**Tensile Strength, Yield** (Type 1, 0.125”, 0.2”/min)	**Tensile Modulus** (Type 1, 0.125”, 0.2”/min)	**IZOD Impact, notched** (Method A, 23 °C)	**Heat Deflection** (HDT) @ 264 psi
Unit	*MPa*	*MPa*	*J/m*	*°C*
PC	30-40	1944-1958	28-73	127
PC/ABS	41	1900	196	96
PA6	28,9-49,3	1817-2232	43-106	93
PA12	28-32	1138-1282	53-135	82
PA12CF	28,8-63,4	2300-7515	21.4-85	143
Ultem1010	42-64	2200-2770	48-120	213
Ultem 9085	33-47	2150-2270	48-120	153
PPSF	55	2100	58.7	189

It is imperative to carry out tests both along the fibers and in the transverse direction. We point out that according to the results of the most studies, it turns out that the strength along the fibers is 2-3 times higher. There is also a serious problem with the choice of "printing temperature" and adhesion between layers of filament. With the wrong choice of temperature parameters for printing on FDM printers, strength can decrease by an order of magnitude. This is especially true for shearing or bending. As a result of shear and bending studies of a model printed on an FDM printer, destruction occurs, as a rule, along the fibers (see Figure 8).

Figure 8. Test result of the FDM printed model.

It is necessary to test additionally the strength of critical parts. Of course, there are standardized strength assessment methods described in ISO 527, ASTM D638-02a and others. However, this approach entails significant additional costs.

Below we describe simple methods for studying printed models, which do not require large expenditures and can be carried out using the simplest laboratory equipment. Let us present some well-known relations.

To determine the ultimate tensile stresses, the following formula is used:

$$\sigma_u = \frac{F_{\max}}{A}, \qquad (1)$$

where σ_u is the limit of temporary resistance, Pa; $F_{\max}$ – ultimate load, N (maximum load before failure); $A = b \cdot h$, $A = b^2$ is the sample area, m^2; b is the width of the section of the sample (beam), m; h is the height of the section of the sample (beam), m.

To obtain the allowable (permissible) stresses, the following relation is usually used:

$$[\sigma] = \frac{\sigma_u}{K_S}, \qquad (2)$$

where $K_S = 2.5 \div 3.0$ is the safety factor for ultimate stress.

We point out that in addition to tensile studies, it is also desirable to perform shear (Figure 9) and bending studies (Figure 10).

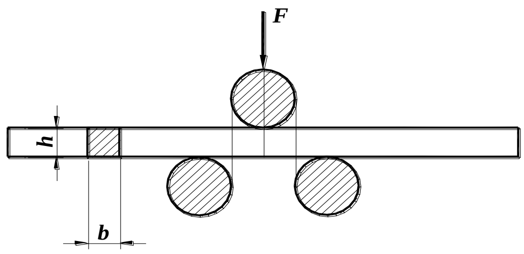


Figure 9. Scheme of testing the sample for shear strength.

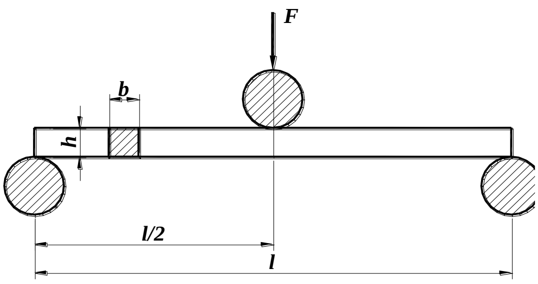


Figure 10. Scheme of testing the sample for bending strength.

The following formula can be used to determine shear stresses:

$$\tau = \frac{F_{max}}{A} = \frac{F_{max}}{b^2}. \qquad (3)$$

When designing gears, the issues of the bending strength σ_F and the contact strength σ_H are very important. These issues are widely covered for gears made of metals. However, these issues have not been sufficiently studied for plastic wheels, especially by 3D printing.

To determine the ultimate bending stresses, the following formula is used:

$$\sigma_{F\,lim} = \frac{M_{max}}{W} = \frac{3 \cdot F_{max} \cdot l}{2 \cdot b^3}; \qquad (4)$$

where $M_{max} = 0.25 \cdot F_{max} \cdot l$ is ultimate bending moment, Nm; l is sample (beam) length, m; $W = \frac{b \cdot h^2}{6} = \frac{b^3}{6}$ is axial section modulus, m^3.

The contact strength can be determined by the following simplified formula:

$$[\sigma_H] = \frac{\sigma_{H\,lim}}{K_S} Z_R Z_V, \qquad (5)$$

where Z_R is the coefficient that takes into account the roughness of the tooth surface; Z_V is the coefficient taking into account the circumferential velocity; $\sigma_{H\,lim}$ is the endurance limit.

Note that for steel teeth, this limit depends on the hardness of the teeth surface, as well as on the number of load cycles. Apparently, the situation with the strength of a 3D printed tooth will be similar.

We mention separately the issue of measuring the hardness of printed products, whose manufacturing is regulated by ISO 2039-1 standards; ISO 2039-2 (ASTM D785). Moreover, for critical designs of 3D printed gears, it is advisable to perform additional durability tests.

4. CONCLUSION

The paper considers the issues of optimizing models for 3D printing, in time, in geometry (accuracy) of the resulting model, in terms of strength, and also in terms of manufacturing cost.

Reducing the time spent on the manufacturing of the final part can be achieved through the choice of technology and printing parameters, as well as by optimizing the 3D model at the development stage. When choosing a printing technology, one should take into account not only the speed of printing, but also the duration of additional operations. As a rule, to speed up the printing process one has to sacrifice the accuracy and surface quality (the accuracy increases with decreasing of the print speed). The task of the designer is to select the manufacturing parameters to ensure the required quality of the geometry (accuracy) with an acceptable duration of the manufacturing process. Ensuring the required strength of the part as a whole depends on the choice of filling method. The introduction of voids, as well as special infill patterns, leads to a decrease in the strength of the printed part. In some cases the infill patterns can be non-optimal (especially obtained in automatic mode). Often, when optimizing a model, taking into account the strength parameters, it is necessary to adjust the internal volume of the model constructively, taking into account the nature of the loading applied to the product. Optimization affects the cost of manufacturing a model, which is formed as a compromise.

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