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Studying the possibility of using additive technology methods in manufacturing hydraulic machine parts

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Abstract

This study aims to enhance the technological capabilities of additive manufacturing and to assess their applicability in the repair and maintenance sector of the agro-industrial complex of Kazakhstan. The research investigates the feasibility of fabricating hydraulic machine components, particularly gear pump (GP) parts, using additive methods. The approach integrates concepts of additive manufacturing, materials science, mechanical engineering, design and strength assessment, and computer simulation. An experimental case study was conducted on a GP shaft-gear, produced via the FDM method on a Raise3D Pro Plus 3D printer. Finite element analysis in SolidWorks demonstrated that the printed shaft-gear withstands operational loads, with maximum stress of 18.45 MPa, remaining within acceptable limits for polymer-based 3D printing materials. Stress calculations for PLA specimens further confirmed that both stresses and deformations are below critical thresholds, ensuring operational reliability. The novelty of this work lies in validating the structural integrity of functional pump components produced by additive manufacturing, which has been insufficiently studied in repair applications. The results provide a scientific basis for expanding the use of additive technologies in hydraulic machinery and highlight their potential to improve efficiency and cost-effectiveness in industrial repair processes.

Keywords: 3D printing, Additive technologies, Deformation, FDM method, Gear pump, Modeling, Stress, Wear.

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1. Introduction

Hydraulic machines are machines that impart mechanical energy to the fluid flowing through them (pumps), or receive part of the energy from the fluid and transfer it to the working element for useful use (hydraulic motors) [1, 2]. Pumps are one of the most com-mon types of hydraulic machines used in almost all the industries, in particular mechanical engineering, construction, mining, oil and gas engineering, agriculture, etc. The studies conducted in the conditions of mechanical engineering and mechanical production of servicing entities of the agro-industrial complex of the Republic of Kazakhstan showed that one of the widely used products in agricultural engineering was hydraulic machines, in particular GP. It was also revealed that GP parts were most often sent for repair and restoration. It was established that the main causes of GP failures were the opening of the contact of the gear teeth during pump operation, poor assembly, wear of bushing parts, thrust bearings, gear teeth, etc.

It is known that gear pumps do not react as strongly to contamination of hydraulic oil as axial piston pumps, so they are easier to maintain. However, they are sensitive to wear that occurs due to foreign inclusions entering the working chambers or due to in-creased friction between components. This is where the first and most common break-down of this type of device comes from: wear on the surfaces of the working chamber parts. When wear occurs in the friction between the gear teeth and the walls of the working chambers, as well as between the ends of the teeth and the thrust plates, this leads to increasing the gaps. As a result, leaks from the discharge chamber back to the suction chamber increase, which significantly reduces the volumetric efficiency of the device. As a result of wear, the pump can retain its operability but with reduced flow and pressure indicators.

There is a major problem in the conditions of machine-building and mechanical production of servicing entities of the agro-industrial complex of the Republic of Kazakhstan, associated with the absence of the necessary technological equipment, tooling, and tools for performing repair and restoration work [3]. To solve this issue, it is necessary to develop and implement new approaches using updated equipment and technologies that ensure the efficiency of machine-building enterprises in manufacturing and repairing machine parts.

A promising solution is the technology of additive manufacturing, which has emerged in recent decades and plays both technological and organizational roles in ma-chine repair. With the introduction of additive technologies, the need to update pump de-signs increases, as these methods can significantly enhance device functionality by improving structural flexibility. Since additive manufacturing enables the production of complex-shaped parts, it paves the way for geometric and engineering improvements in pump components. Optimizing pump design using these technologies can improve over-all device performance and efficiency.

The technology of three-dimensional (3D) printing emerged in the late 1980s. One of the pioneers in this field was 3D Systems, which introduced the first commercial stereo-lithography machine – Stereolithography Apparatus (SLA) – in 1986. Until the mid-1990s, 3D printing was primarily utilized in research and development, particularly in defense-related industries. Early machines, including laser-based stereolithography (SLA) and selective laser sintering (SLS) systems, were prohibitively expensive, and the range of available modeling materials was extremely limited.

The rapid development and integration of digital design technologies such as Computer-Aided Design, Computer-Aided Engineering and Computer-Aided Manufacturing significantly accelerated the advancement of additive manufacturing. Today, it is difficult to identify a field of material production where 3D printing technologies are not applied to some extent. Digital 3D technologies have enabled the precise reproduction of complex spatial geometries, engineering structures, and functional mechanisms.

As noted in Kovalev and Kovalenko [4], the economic efficiency of 3D technology lies in its high quality, non-alternative nature, waste-free production, and significant cost reduction in serial and mass production. At the same time, 3D technologies represent a test of the intellectual lev-el of science, education, and the professional qualifications of the labor force, as well as the overall level of industrial development.

In work [5] the main capabilities and areas of application of 3D printing are de-scribed. The characteristics of various 3D printers are compared. A description of the main stages of preparing a model for printing is provided. The capabilities of software for 3D modeling and printing are indicated.

Work [6] examines the concepts, as well as the advantages and disadvantages of additive manufacturing, provides a general sequence of the technological process, and ex-amines various additive manufacturing technologies.

Work [7] considers the most popular technologies of additive manufacturing of parts by precision engineering enterprises. Economic and statistical data of the additive technologies market in the world are described.

Work [8] studies the possibility of introducing additive technologies into industrial production and features of the layer-by-layer synthesis process. The methodological basis of the work is a systematic approach to studying and describing the relationships between the operational properties of a part and the technological conditions of three-dimensional printing. The scientific novelty and practical significance of studying additive technologies for Kazakhstan are obvious. First of all, this is the development of a new area of technological knowledge of industrial production.

Work [9] considers methods of obtaining nickel-based metal powder materials for use in various fields of industry and mechanical engineering. Ways to increase the technological strength of parts made of nickel-based powders are outlined. It is noted that additive technologies are fundamentally new methods in the production of various types of products, including metal ones. Their use allows both developing products “from scratch” and processing the existing ones. The manufactured material has mechanical and physical characteristics identical to the properties of the material obtained by traditional forging or casting.

Paper [10] presents an overview of the current state of additive technologies. A brief history of emergence of additive technologies is given. The known technologies, their ad-vantages and disadvantages are analyzed. The information of the main polymeric materials used in 3D printing is given. Based on the results of experimental studies, the possibility of using additive technologies in manufacturing low-power turbogenerator impellers is shown.

Article [11] considers the issues related to materials used in the repair of agricultural machinery. Particular attention is paid to updated repair methods that are directly related to additive technologies. The main methods of using these technologies, their advantages and features in the repair of equipment operating in the agricultural industry are de-scribed.

Paper [4] considers the use of additive technologies, as well as selective laser sinter-ing methods. Ways to improve and develop new additive technologies, as well as the use of selective laser sintering technologies are outlined.

Paper [12] considers the use of three-dimensional printing in manufacturing metal products. The paper presents the basic principles of operation of three-dimensional printing, its advantages and disadvantages. It also considers various types of three-dimensional printing used to manufacture metal products. The main aspects of using this method and its impact on the quality and functional properties of manufactured parts are defined. An analysis of using additive technologies in the process of manufacturing metal parts for mechanical engineering is also carried out. The results of studies are presented that allow assessing the impact of these technologies on the quality and functional properties of products.

Work [13] describes the complex relationship between AM processes, microstructure and the resulting properties of metals. It explains the fundamentals of laser beam melting, electron beam melting and laser metal deposition and presents commercially available materials for different processes. Typical microstructures for steel, aluminum and titanium produced by additive manufacturing are also presented. Particular attention is paid to the specific AM grain structures resulting from the complex thermal cycle and high cooling rates. The properties developed as a result of the microstructure are developed under static and dynamic loading. According to these properties, typical application areas of materials and methods are presented.

Work [14] summarizes the knowledge on the process parameters for FDM in D-printing and various types of material property testing for PLA. This technology is continuously optimized and adopted by an increasing number of research institutes, companies and customers, in the aspects of cost, functionality, product quality and production time. Trends in this field for future FDM research are outlined.

Paper [15] provides a detailed review of both thermoplastic polymers and FRCs printed using FDM technology, including the effects of printing parameters such as layer thickness, infill pattern, raster angle, and fiber orientation. The most common defects of printed parts are studied, in particular, void formation, surface roughness, and poor adhesion between the fiber and the matrix. The review discusses in detail the effectiveness of chemical, laser, thermal, and ultrasonic treatments to minimize these drawbacks.

Paper [16] demonstrates extrusion 3D printing that combines the strengths of FDM and UV-assisted 3D printing. Using photopolymer extrusion in combination with two additional rotation axes, the printer developed in this work allows not only traditional layer-by-layer printing but also free-form printing. Fumed silica is used as a filler to control the material viscosity for proper extrusion and curing. Mechanical tests were carried out on objects printed using different filler concentrations in photopolymer.

Paper [17] reviews the research progress in the area of factors affecting the results of 3D printing of the fused deposition modeling process. The review presents a comparison of the critical parameters and characteristics that determine the FDM parameters, the effects of each parameter and their interactions with the other parameters. The information of the filament production process, filament material types and FDM printing parameters are provided. This study also identifies several important areas of previous and future re-search to optimize and characterize the critical parameters of the FDM printing process and FDM filament production.

Paper [18] presents an overview of digital light processing (DLP) technology and its recent advances; in particular, the review covers the properties of photopolymers, the preparation of ceramic and metal raw materials and the light-matter interaction mechanism underlying the printing and post-processing stages.

In work [19], a systematic literature search is conducted based on the classification by the type of polymer for 3D printing. The most significant process parameters that are considered to affect the tensile, compressive, bending or impact strength of FDM samples are discussed taking into account the results presented in the literature. The necessary distinction is also made between mechanical properties of the material and test samples (as specified by the manufacturers and in the experiments) and the mechanical behavior of the final FDM part.

The results of the studies show that additive technologies for the production of various types of parts are currently developing rapidly, in particular, due to the growth of the range of various powder materials. The analysis also shows that in many cases the use of additive technologies allows obtaining products that are more economically advantageous, with better quality indicators and with acceptable parameters (weight, shape complexity). It has been found that additive technologies are preferable when, for example, it is necessary to restore the damaged shape of fairly expensive products, as well as when manufacturing or repairing worn parts requires the use of various technological equipment that is not always available at the production site.

In general, the obtained theoretical knowledge confirms the relevance of using additive methods in manufacturing and repairing hydraulic machine parts, in particular pumping equipment. This forms a solid basis for the practical part of the study.

In this regard, scientific research aimed at manufacturing hydraulic machine parts for agricultural machinery is relevant.

2. Materials and Methods

2.1. Experimental studies of the manufacturing process of a gear shaft part using the FDM method

Figure 1 shows a sketch of the GP50 shaft-gear part.

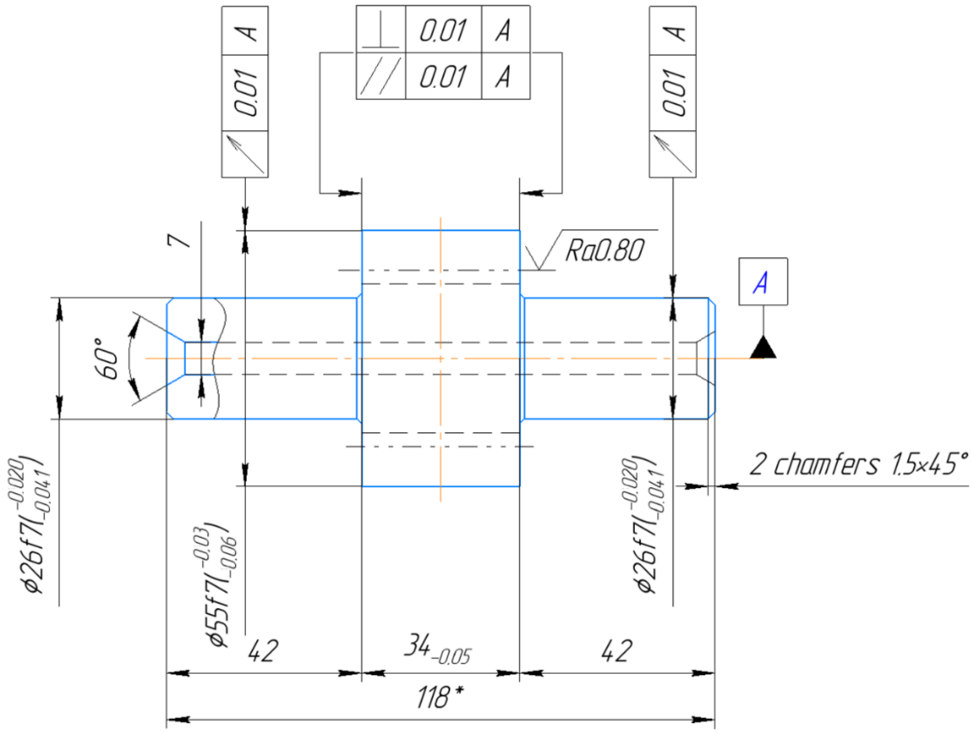

Figure 1.
Sketch of the GP50 shaft-gear part.

The gear shaft was designed in the CAD software for subsequent 3D printing and imported into the IdeaMaker software designed for the Raise3D Pro Plus 3D printer (Figure 2).

Figure 2.
Raise3D Pro Plus 3D Printer.

Figure 3 shows the model imported into the IdeaMaker software.

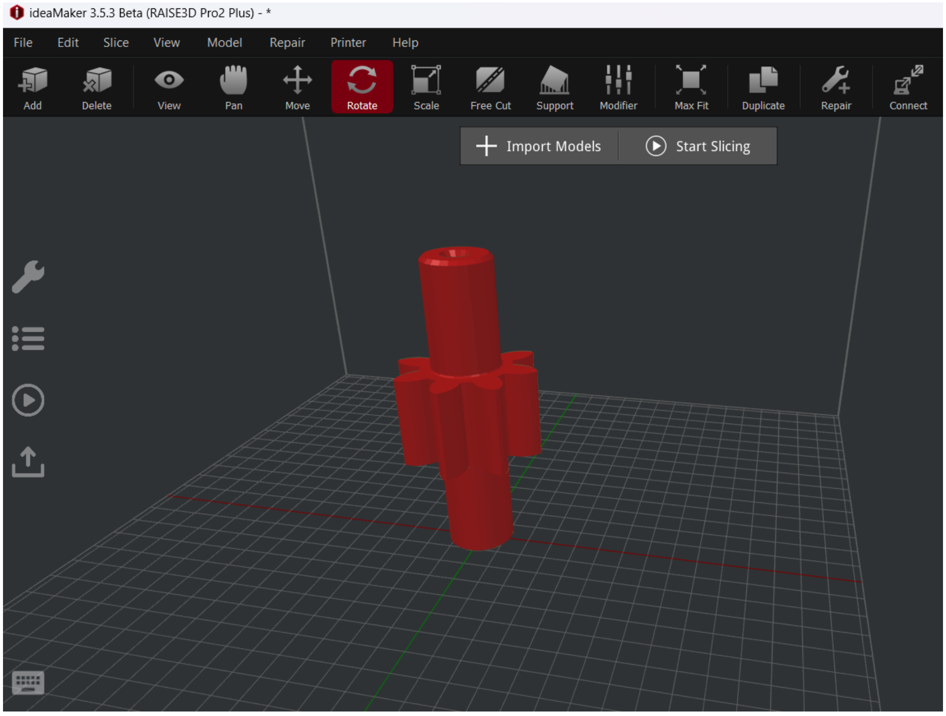

Figure 3.
Model imported into the IdeaMaker software.

In the IdeaMaker program, the filling of the internal cavity of the model can be adjusted by changing the Filling Density parameter (Figure 4).

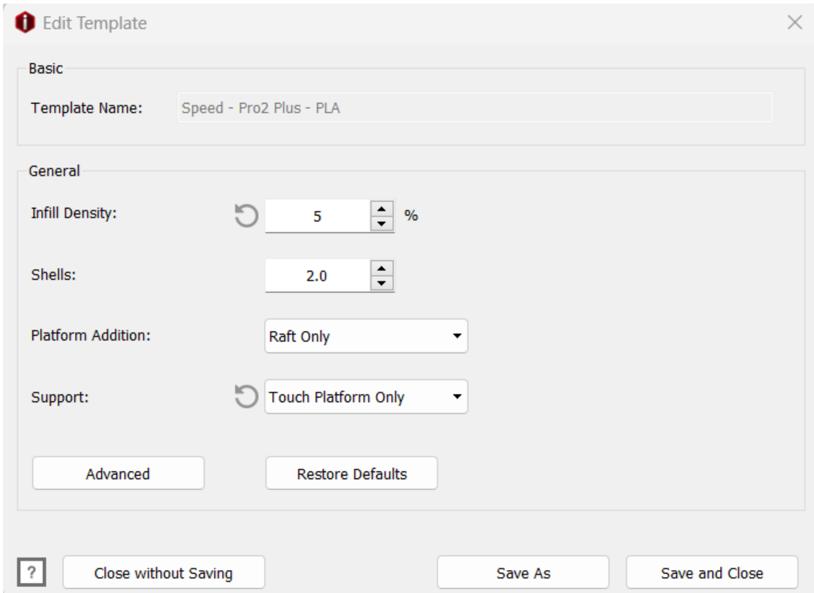

Figure 4.
Filling of the internal cavity of the model is adjusted by the Filling Density parameter.

The model imported into the IdeaMaker program was printed on a Raise 3D Pro Plus 3D printer (Figure 5). The Raise 3D Pro Plus printer uses the FDM method. The FDM (Fused Deposition Modeling) method is a layer-by-layer 3D printing method in which a thermoplastic material (e.g. PLA, ABS, PETG) is heated and extruded through a nozzle, and then applied in layers to form the finished model.

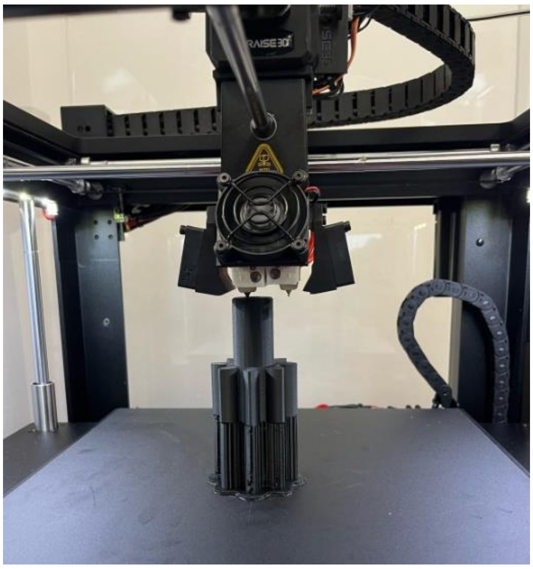

Figure 5.
– 3D printing process on the Raise3D Pro Plus printer.

Figure 6 shows the finished shaft-gear part printed on the IdeaMaker 3D printer.

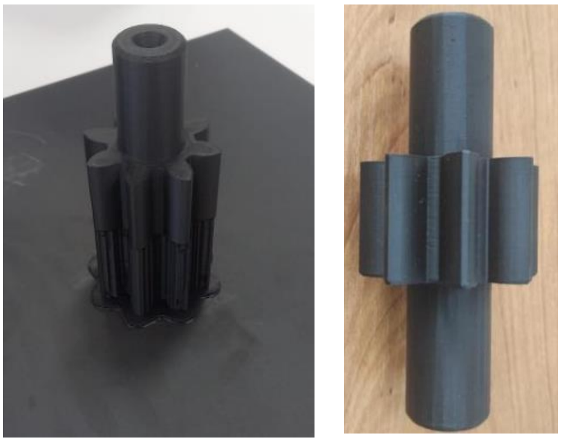

Figure 6.
Finished shaft-gear part printed on the IdeaMaker 3D printer.

The effect of the degree of filling the internal cavity of models printed on the Raise3D Pro Plus 3D printer on printing time (Figure 7) was studied, as well as the material consumption (Figure 8).

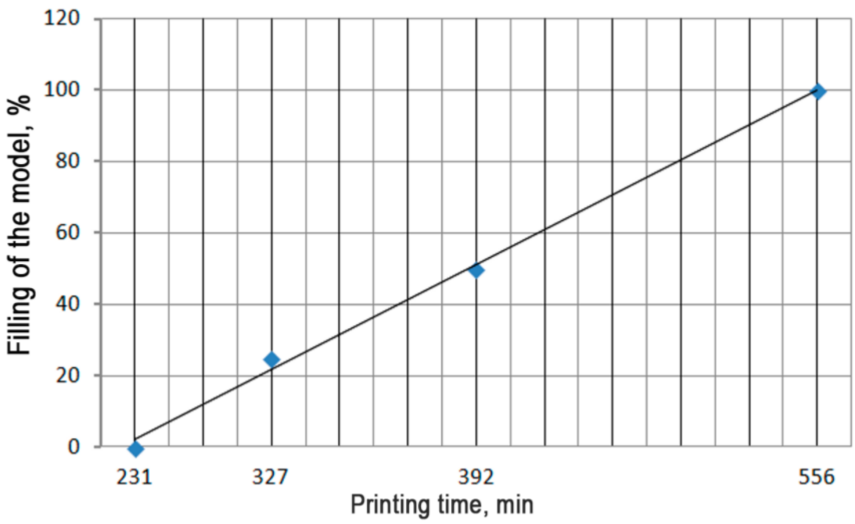

Figure 7.
Filling the internal cavity effect on the printing time.

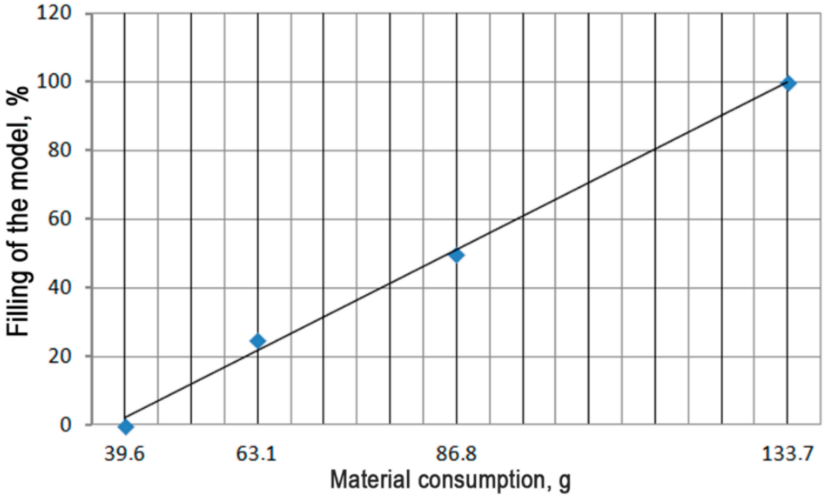

Figure 8.
Filling the internal cavity effect on the material consumption.

The study showed that with increasing the filling density from 0% to 100%, the printing time significantly increased. The greatest increase occurs when moving from 50% to 100%, which is caused by a more complex internal structure of the model at the maximum filling density. Material costs also increase with increasing the filling density. As with the nprinting time, the greatest increase in material costs is observed when moving from 50% to 100%, which is also caused by the increased density of the internal structure. Both indicators: the printing time and material costs, grow almost synchronously with increasing the filling density, but increasing material costs is more pronounced. This indicates that with increasing the filling density, the material and time consumption increases significantly, which must be taken into account when planning 3D printing to optimize resources.

2.2. Modeling and strength calculating of the gear shaft part manufactured by the FDM method

Figure 9 shows the GP50 model with the mounted gear shaft.

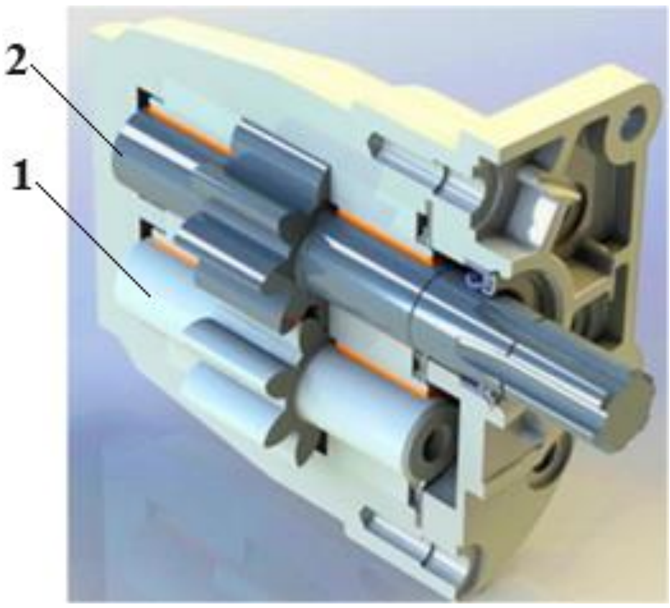

Figure 9.
GP50 model with the mounted gear shaft: 1 – driven shaft-gear made of plastic; 2 – pinion shaft-gear.

Let's simulate the operation of the GP50 to calculate the strength of the gear shaft manufactured using the FDM method. Figure 10 shows simulating the operation of two gear shafts for strength calculation.

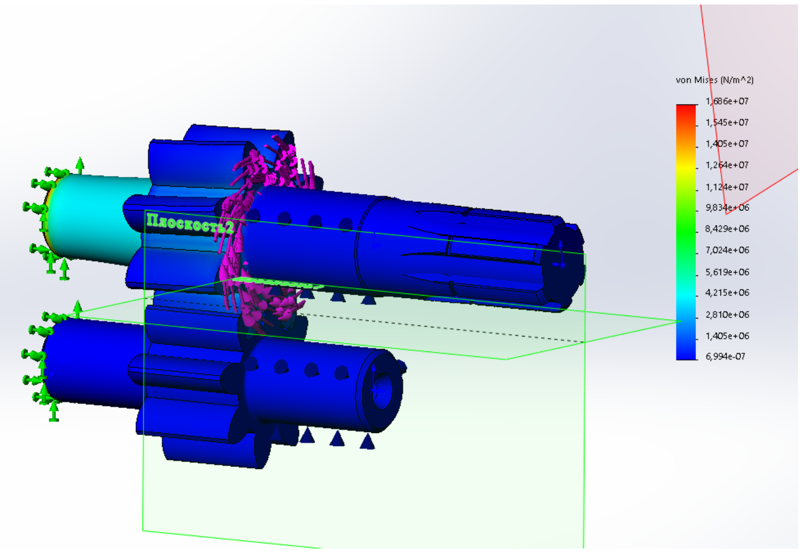

Figure 10.
Simulating the operation of two gear shafts for strength calculation.

The gear shaft is made by the 3D printing method using PLA plastic. However, in the program, the ABS material was chosen as an alternative to PLA plastic. The purpose of the calculation was to determine whether the structure could withstand the operating torque. The driven shaft is secured in the housing on both sides (green arrows in the image); this simulates a support in bearings (see Figure 9, item 1).

A torque of 7.96 N·m is set on the drive shaft - this simulates a real load during operation (see Figure 9, item 1). The torque of 7.96 N·m corresponds to the power of 2500 W (or 2.5 kW) with the rotation speed of 3000 rpm. This proves that the torque was calculated based on the power of 2.5 kW. To show the reality of the load, athepower of 2.5 kW was chosen, which corresponds to the standard power level for such mechanisms.

The shaft and gear are modeled as a single solid part, since they will be printed together. The mating between the gears is set taking into account the real contact between the teeth. Figure 11 shows a graph of the stress dependence according to the von Mises criterion.

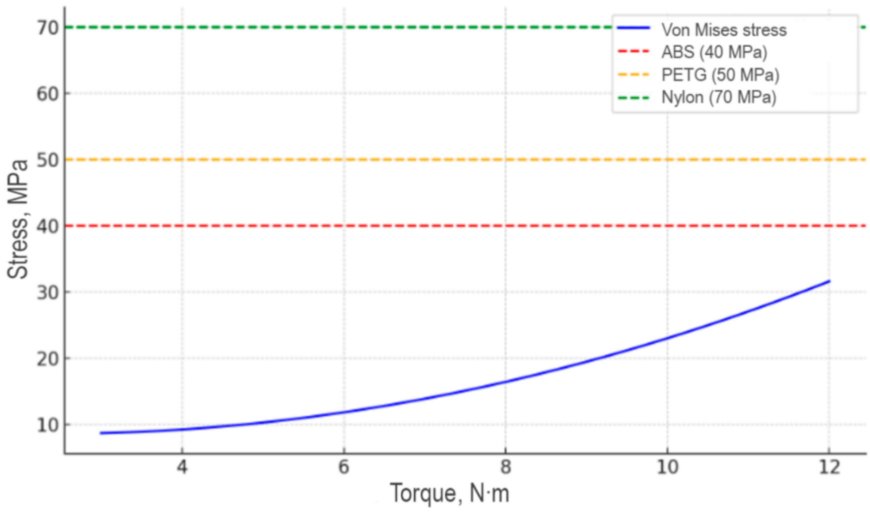

Figure 11.
Stress dependence according to the von Mises criterion

The stress distribution according to the von Mises criterion is used as an indicator for assessing the strength of plastic and metal parts (see Figure 11). The maximum stress observed in the model was 18.45 MPa (marked in red on the gear), which is well within the permissible limits of commonly used 3D printing plastics. For instance, ABS can with-stand approximately 40 MPa at break, PETG about 50 MPa, and Nylon up to 70 MPa. These results indicate that the structure is safe and reliable when manufactured from standard durable polymers.

The obtained stress values indicate that the design is safe and reliable when printed using standard durable plastics. Although the pump assembly includes components such as the housing, cuffs, and covers, they were excluded from the strength calculation, as they do not participate in torque transmission and are not subjected to significant mechanical loads. This exclusion allowed the analysis to focus on critical nodes and reduced simulation time without compromising result accuracy.

The simulation results confirmed that the shaft-gear component can withstand operational loads (see Figure 10), making the design suitable for additive manufacturing, pro-vided that appropriate material is selected. Including the non-load-bearing components in the calculation is unnecessary, as they do not affect the strength of the gear mechanism.

Figure 12 presents the modeling of the shaft-gear used for analyzing relative deformations.

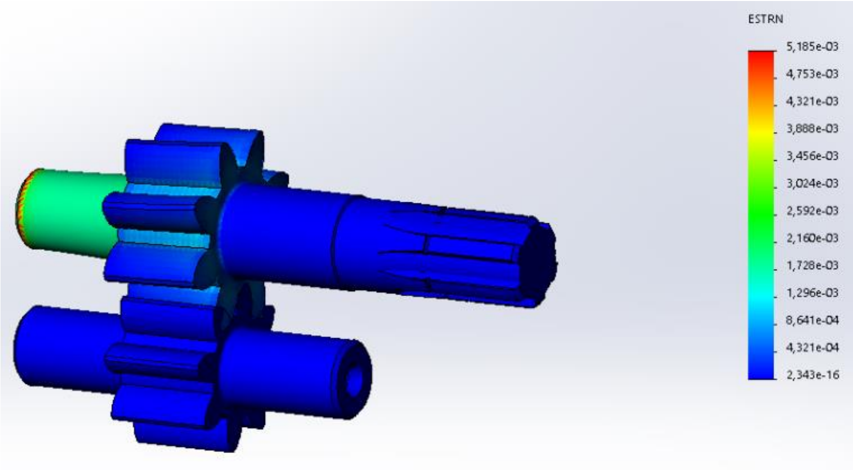

Figure 12.
Modeling of the shaft-gear for calculating relative deformations.

The calculation of relative deformations (ESTRN) of two connected gear shafts during torque transmission was performed in the SolidWorks Simulation program with the following specified conditions: the speed was 3000 rpm; the power was 2500 kW; the torque was 7.96 N·m.

Figure 13 shows a graph of the distribution of relative deformations along the length of the gear shaft.

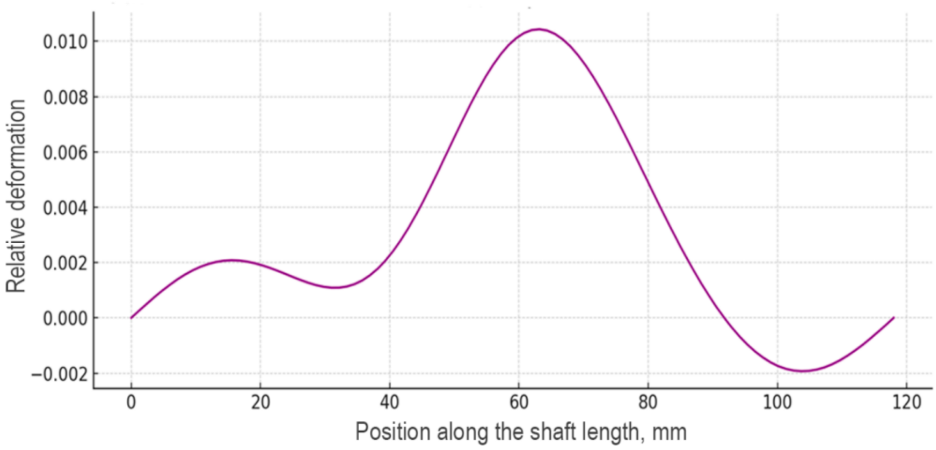

Figure 13.
Distribution of relative deformations along the length of the gear shaft.

The main contact area of the teeth is painted dark blue, which indicates minimal deformations in this area (see Figure 12). This is a good indicator and means that the gears in the engagement area are practically not subject to unwanted plastic deformation and are distributed evenly in the contact.

When transmitting different values of the torque and speed, the design of the shafts and gear connection operates stably, and deformations in the engagement are minimal. Particular attention should be paid to the ends of the shaft, where local deformation maxima are observed; perhaps it is worth rechecking the fastening conditions or reinforcing this area.

Figure 14 shows the modeling of the shaft-gear for calculating relative deformations.

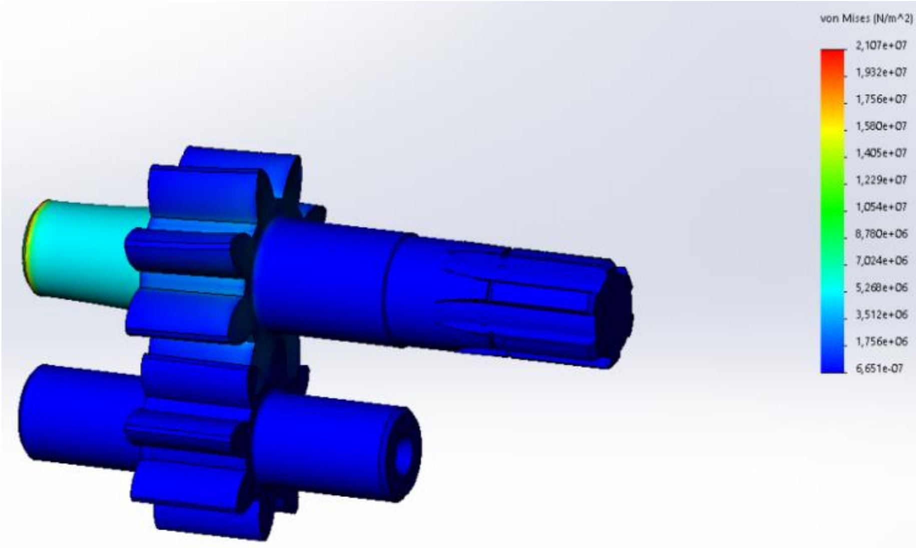

Figure 14.
Modeling of the shaft-gear for calculating relative deformations.

The simulation results show that when the rotation speed decreases from 3000 rpm to 2400 rpm, the torque increases. At 3000 rpm, the torque is 7.96 N·m, and at 2400 rpm it is approximately 9.95 N·m. This is because when the rotation speed decreases, the angular velocity decreases; so, to maintain the power, the torque increases. However, this does not cause overload: the design has a safety margin, and it can easily withstand such a load. The difference is not critical and does not require revision of the model.

Figure 15 shows the simulation of the gear shaft for calculating URES.

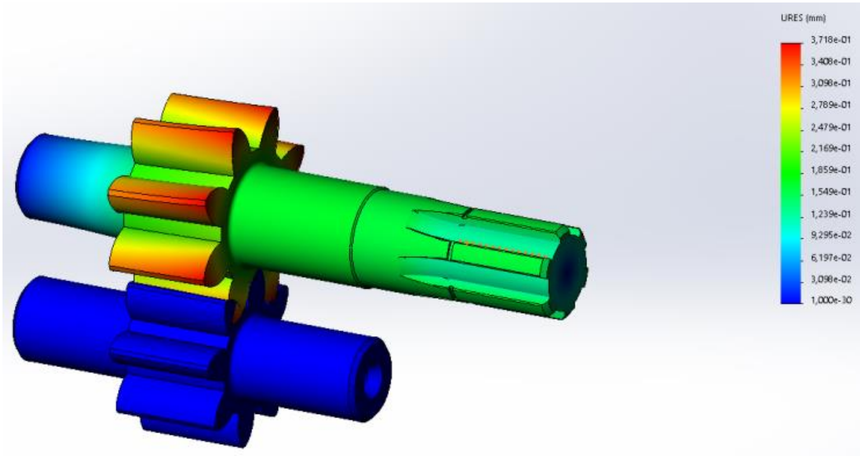

Figure 15.
Simulation of the gear shaft for calculating URES.

Figure 16 shows the dependence of displacements along the length of the gear shaft.

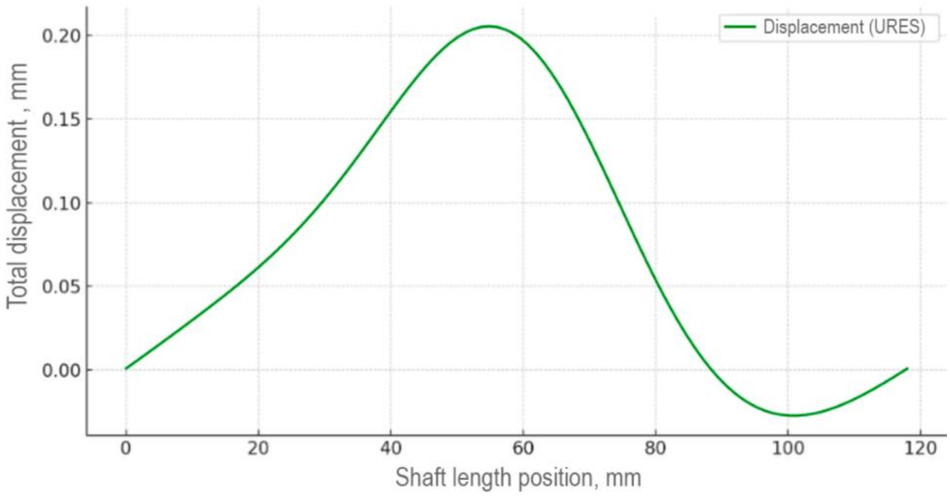

Figure 16.
Dependence of displacements along the length of the gear shaft.

The graph in Figure 16 presents the displacement values (URES, mm), which repre-sent the total spatial displacement of each point on the part due to the applied load and boundary conditions. The analysis of the shaft-gear simulation results for URES (see Figure 15) reveals that the maximum displacement reaches approximately 0.3718 mm, ob-served in the red-colored regions. These areas correspond to the gear teeth near the edge and the free end of the shaft, where the geometry is less constrained, allowing greater de-formation under load.

The minimum displacement, approaching ~1.00e-30 mm, is indicated in dark blue and occurs in regions close to or directly constrained by fixed supports. The central por-tion of the shaft and the key exhibit moderate displacement, represented by green-yellow zones, reflecting typical working deformations resulting from torque transmission and shear forces during tooth engagement.

This behavior indicates that the gear teeth and the shaft's free end are most suscepti-ble to displacement – an expected outcome during load transmission and rotation. Nev-ertheless, the contact zones of the gear teeth remain relatively stable under load, suggest-ing that the structure can sustain the applied forces without undergoing critical displace-ment. If these deformations fall within acceptable limits based on engagement conditions, tolerances, and backlash criteria, the design can be considered operational. Otherwise, structural modifications – such as reinforcement of the shaft, redesign of supports, or ad-justments to the gear geometry– may be necessary.

Overall, the model demonstrates typical deformation patterns for gear assemblies under load, emphasizing that displacement concentrates at the gear edges and shaft ends. These factors must be considered in engagement analysis and bearing selection to ensure that displacements remain within permissible tolerances.

3. Results and discussion

3.1. Stress calculation for the PLA gear shaft

Stress calculation for the PLA gear shaft Initial data. The total length is 118 mm; the gear diameter is Ø55 mm; the centering plug diameter is Ø26 mm; the center hole diameter is Ø7 mm; the gear rotation radius r is 27.5 mm (0.0275 m); the weight is 0.73 kg.

The centrifugal force is calculated using the formula:

$$F_c = m \cdot r \cdot \omega^2,$$

where,

$$\omega = \frac{2\pi \cdot 3000}{60} = 314{,}16 \text{ rad/s.}$$

$$F_c = 0{,}73 \cdot 0{,}0275 \cdot \left(314{,}16\right)^2 = 1982{,}5 \text{ N.}$$

Calculation of stress on the cylindrical surface

The cylinder area is:

$$A = 2\pi \cdot R \cdot b = 2 \cdot 3{,}14 \cdot 0{,}0275 \cdot 0{,}034 = 0{,}005875 \text{ m}^2.$$

The stress on the cylindrical surface is calculated using the following formula:

$$\sigma = \frac{F_c}{A} = \frac{1982,5}{0,005875} = 337,470 = 0,337 \text{ MPa.}$$

The safety factor (n) for a part manufactured from PLA was calculated using the ma-terial's yield strength and the maximum equivalent stress obtained from the simulation. For PLA, the yield strength is approximately 50 MPa. Given the maximum von Mises stress of 0.337 MPa, the safety factor is n=148. A safety factor of approximately 148 indicates a significant strength reserve, con-firming that the component is structurally sound under the applied centrifugal load.

3.2. Contact Stress Analysis in Gear Engagement

To evaluate the contact loading on the gear teeth, the following parameters were used: Gear diameter: d=55 mm; Number of teeth: z=11; Tooth rim width: b=34 mm; Module of engagement: m = d/z=5 mm; Applied torque: M=3 Nm. The circumferential force acting on the gear teeth is determined from the torque:

$$F_t = \frac{2M}{d} = \frac{2 \cdot 3}{0,055} = 109,1 \text{ N.}$$

Contact stress:

$$\sigma_H = \sqrt{\frac{4F_tE}{\pi bR}},$$

where

$$E = \frac{E}{1-\nu^2} = \frac{3500 \cdot 10^6}{1-0,35^2} = 4,14 \cdot 10^9 \text{ Pa,}$$

$$R = \frac{2}{d/2} = \frac{4}{d} = \frac{4}{0,055} = 72,7$$

$$\sigma_H = \sqrt{\frac{4 \cdot 109,1 \cdot 4,17 \cdot 10^9}{\pi \cdot 0,034 \cdot 72,7}} = 0,484 \text{ MPa.}$$

Bending Stress of Gear Teeth (According to Lewis Formula)

To evaluate the bending stress acting on the gear teeth, the Lewis equation is used:

$$\sigma_F = \frac{F_t}{b \cdot m \cdot Y},$$

where F_t = 109.1 N – tangential (circumferential) force; *b*=34 mm – face width of the gear; m=5mm – module of engagement; Y≈0.245 – Lewis form factor for a gear with z=11 teeth (straight spur gear).

Substituting the values:

$$\sigma_F = \frac{109,1}{34 \cdot 5 \cdot 0,245} = 2,62 \text{ MPa.}$$

The analysis indicates that the gear tooth will not fail under the given load, provided that no impact loads or overheating occur. The strength evaluation of the shaft-gear component manufactured using the FDM method demonstrates that the resulting stresses and deformations remain within permissible limits, confirming the structural reliability of the part under operational conditions. Stable torque transmission is achieved without the risk of mechanical failure.

Furthermore, the numerical model exhibits a high degree of correlation with experimental data, validating its applicability for strength assessment and for optimizing 3D printing parameters. The results obtained can serve as a basis for enhancing additive manufacturing technologies for similar mechanical components in the field of mechanical engineering.

4. Conclusions

The results of studies conducted under the conditions of mechanical engineering and production at servicing entities of the agro-industrial complex of the Republic of Kazakhstan indicate that gear pumps (GP) are among the most widely used components in agricultural machinery. The primary causes of GP failures were identified as loss of contact between gear teeth during operation, poor assembly quality, and wear of bushings, thrust bearings, and gear teeth.

A significant issue revealed during the analysis was the lack of appropriate techno-logical equipment, tooling, and instruments required for effective repair and restoration work in these enterprises. To address this problem, the application of additive manufacturing technologies is proposed for both the repair and production of GP components, as well as other parts of agricultural machinery and equipment.

As part of this study, the shaft-gear component of a gear pump was manufactured using Fused Deposition Modeling (FDM) on a Raise3D Pro Plus 3D printer. The strength of the printed part was analyzed using SolidWorks simulation tools. The maximum stress observed was 18.45 MPa, which remains within the allowable range for plastics commonly used in 3D printing. A separate simulation for a PLA gear shaft also confirmed that the stresses and deformations did not exceed acceptable limits, verifying the structural integrity and reliability of the part under operational conditions. Torque transmission was found to be stable, with no risk of failure.

The simulation results demonstrated a high level of correlation with experimental data, supporting the model's suitability for strength evaluation and optimization of 3D printing parameters. These findings confirm that the design is safe and reliable when manufactured using standard high-strength thermoplastics.

Further research is recommended to evaluate the gear shaft component under real operating conditions. Additionally, detailed 3D profilometric, optical, and raster analyses are necessary to investigate the internal structure and surface quality of the printed gear shaft.

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