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# ORGANIZATION OF REVERSE ENGINEERING USING MODERN CALCULATION METHODS IN THE PROCESS OF REPRODUCING A GEARS

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**Purpose:** The main purpose of this article is to present modern possibilities for the reproduction of a machine element. If there are no replacements for the damaged part, and there is no technical documentation, then the only options is to use reverse engineering (RE) methods to reproduce it.
**Design/methodology/approach**: On the example of a damaged gear, the process of measuring the wheel and manufacturing a physical model using 3D printing. An additional step has been added to the classic reverse engineering process to modify the model to improve its strength.
**Findings:** Strength analysis was carried out in the Abaqus program using the finite element method (FEM). Based on the results obtained, it was proposed to change the tooth profile of the gear, which will improve its durability.
**Research limitations/implications**: An extension of the proposed scheme may be a modification of the production process in order to implement the reverse engineering method to the serial production of machine elements.
**Practical implications:** The use of a modified reverse engineering (RE) process will not only allow the components to be reproduced but will also allow extended uptime of the components, and this will reduce production costs.
**Originality/value:** The proposed new reverse engineering process can be successfully used to reconstruct machine components with even very complex shapes. The digital model obtained as a result of scanning has been used to improve the geometry of the toothed rim, but it can be successfully used for other analyses, research, or calculations.

**Keywords:** reverse engineering (RE), rapid prototyping (RP), finite element method (FEM), reconstruction process, gear.

**Category of the paper:** Research paper.

## 1. Introduction

Reverse engineering (RE) aims to obtain a digital form of a physical model and then produce a copy of it with the same or expected geometrical and strength parameters. This process consists of two main stages, including the digitization of the real object and the production of a physical model. Digitization can be realized with using optical scanners or with the help of contact measurements, depending on the availability of devices and the expected accuracy. Then the obtained measurement result is checked and corrected in CAD programs until a geometrically correct, digital CAD model of the reproduced element is obtained. On its basis, it is possible to create a physical copy of the output model, e.g. using rapid prototyping (RP) methods.

Such a basic scheme of the reverse engineering process is in many cases enough for the reconstruction of machine elements that cannot be made using a classical method (Pacana et al., 2018). In addition, the undeniable advantage of this process is the fact that as a result of scanning, a digital model of the element is obtained, which can be modified. Therefore, it was proposed to change the basic RE process by extending it to the CAD model modification stage. A diagram of the extended reverse engineering process is shown in Figure 1, and the added RE process step is highlighted in grey. Modifying a digital model can involve simple dimensional changes, but it can be the result of extensive material, strength, or thermal analysis. CAD models obtained as a result of scanning in the first stage of the reconstruction process can be used to perform numerical calculations of kinematic simulations and to evaluate their durability and reliability. The introduction of the CAD model modification stage significantly expands the possibilities of using reverse engineering methods in production and reproduction processes of even geometrically complicated machine elements.

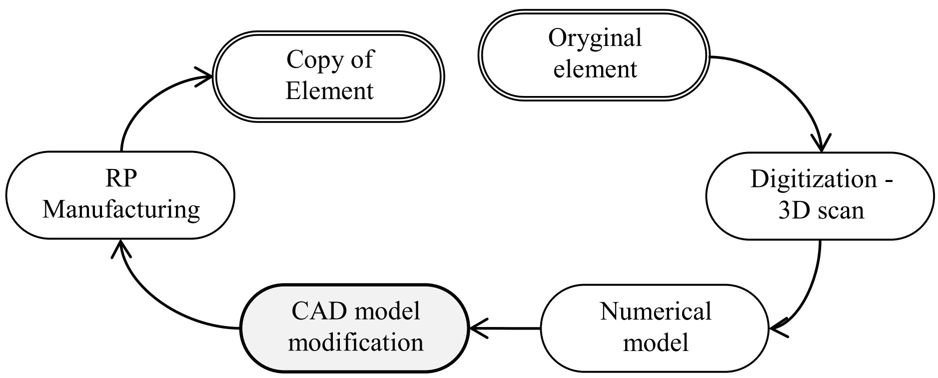


**Figure 1.** Diagram of the RE process with the CAD model modification step (Kachel, 2011).

An example of parts with complicated construction and difficult working conditions are gears. They are used most often in drives and then have an involute profile of teeth, but they are also successfully used in pumps, valves, or control mechanisms (Müller, 1970). The basic line of involute can be subject to multidirectional modifications of geometric parameters in order to increase tooth strength, improve cooperation conditions, quiet running or vibration reduce. Gears usually are made of steel using machining techniques. However, wherever they do not transfer powerful loads, gears made of polymer materials are successfully used. Because then they are made by injection into molds, they often have atypical tooth profiles, difficult to reproduce with classic machining. In the event of gear damage, the correct procedure is to replace the damaged element with the same new one. If the production of substitutes has already been ended or they are not available, it is usually not possible to make a gear with the same geometrical parameters using machining methods. With the development of measurement techniques and additive manufacturing methods, the possibility of making precise copies of damaged gears at a relatively low cost has just appeared (Budzik, 2007). By restoring a corrupted element, can be correct its geometry to increase durability or functionality. This procedure is presented later in the article.

## 2. Digitize the gear model

The reconstruction and modification process of the model was presented on the basis of a gear being part of a household appliance. The gear wheel was made of polymer plastic and was originally mounted in a meat mincer. Unfortunately, during use, there was a situation in which the teeth of this gear were broken. An ad hoc solution to such a situation was to replace the damaged gear with a new one. However, since it was not possible to buy a new gear due to the end of its production, it had to be reconstructed on the basis of the damaged element. In the first stage, it was necessary to scan the used gear in order to obtain its numerical model. This was done using the contact scanning method on a Roland MDX-40 coordinate measuring machine using a special ZSC-1 measuring head.

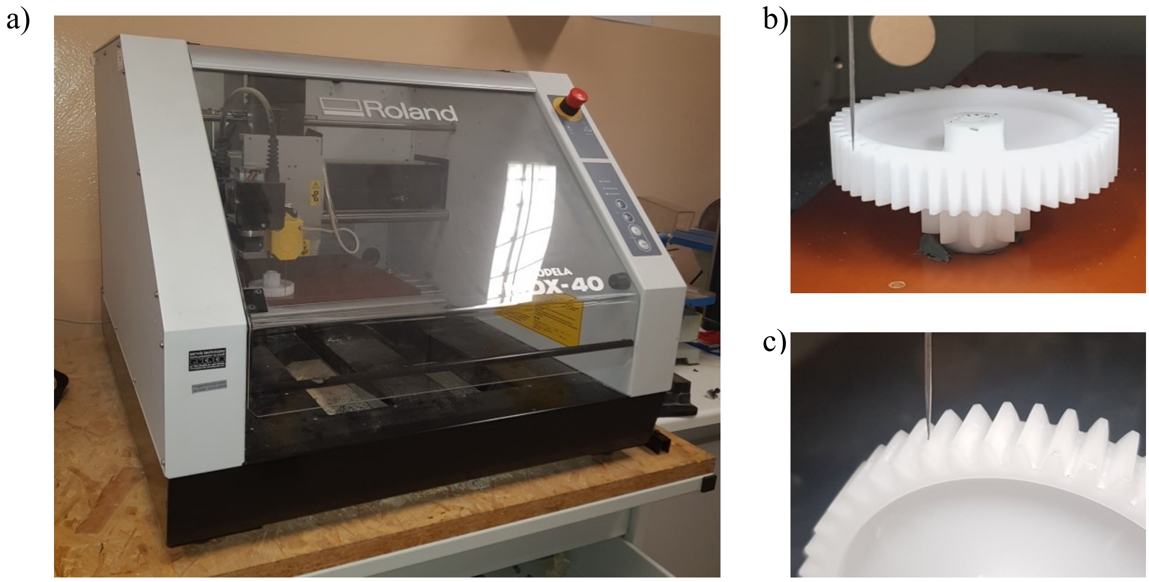


**Figure 2.** Digitization of the model using the contact method: a) Roland MDX-40 measuring machine, b) gear geometry measurement, c) tooth profile scanning.

Since the measuring tip of the head had a very small radius, it was possible to digitize the gear model with high accuracy. In the first step, general measurements of the geometry of the model were made regarding diameters, thicknesses, or rounding radius. This was done in two gear mounts, first where its main axis was parallel to the axis of the measuring tip (Fig. 2b). The second phase of the measurements concerned the measurements of the tooth outline in the direction perpendicular to the model axis (Fig. 2c). For some correct teeth, measurements were made with the highest machine precision possible of 0.04 mm.

Thanks to the contact measurements, both the surface model of the gear and the tooth profiles were obtained (Fig. 3b). The automatically received measurement results had the format of a point cloud and required minor correction. The acquired surfaces had node errors and discontinuities, which were removed directly in the program used to made the measurements. Some errors of the acquired surface for the digitized gear can be observed in the area of its hub (fig. 3).

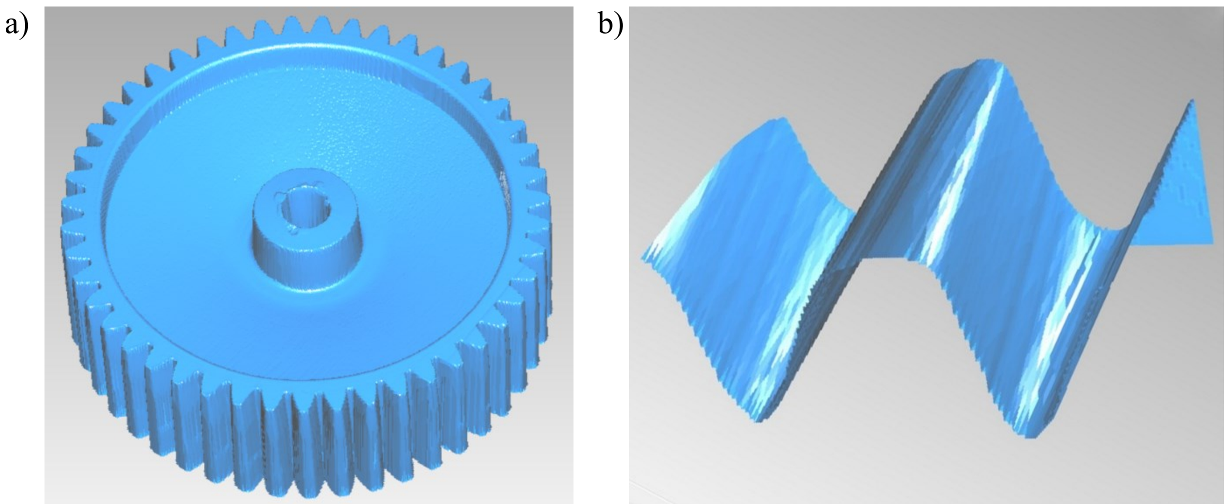


**Figure 3.** Gear scan result: a) digitized surface model, b) profiles of the selected tooth.

The next work on the model concerning its smoothing, connection, matching, and modification was performed in the Autodesk Inventor program. The gear model in places of damage was also supplemented by copying the correct geometry from adjacent teeth. However, the final correction of the toothed rim will be made only after additional strength calculations have been solved. In Autodesk Inventor program, the surface model resulting from scanning was also transformed into a solid model that will be used to produce a new gear using the incremental method.

This program was also used for preliminary measurements of the tooth profiles and the surface of the whole gear. On their basis, the nominal geometric parameters of the toothed rim were determined, and the final shape of the gear was assumed. The tooth module was found to be 2 mm, the number of teeth is 47, and the width of the rim is 12 mm. Comparison of the outline obtained in the measurements with the theoretical ones confirmed that there are teeth in the circle with an outline angle of $\alpha = 20°$. This was not evident results, because the original gear was made by moulding, so the technology did not force the use of tools with this most popular angle of tooth profile for the production of the gear.

On the outer surface of the model was also found information about the material used in its production. It was a commonly used acrylonitrile-butadiene-styrene polymer (ABS). The result of the successful process of reconstructing the gear geometry was its solid model, which can be freely modified in the CAD program.

## 3. Modification of the tooth profile

The goal of modifying the tooth profile is to obtain a gear with greater strength. Changes in the contour of the gear teeth can proceed in different ways, which has been repeatedly described in publications. In the case of the analysed gear, it was assumed that the changed parameter would be the angle of the tooth outline. Such a corrections do not bring too many modifications in the geometry of the tooth rim, but also do not change the axis distance, which would force changes in the entire device. Therefore, for the reproduced gear, numerical calculations were performed using the FEM in the Abaqus program. It is a driven wheel that is part of the meat mincer drive mechanism of the meat mincer. Because this gear was damaged, an attempt was made to improve its strength by changing the profile of the teeth. Three variants of the model were analysed, which differed only in the angle of the involute profile. The value set for the damaged gear of 20° was assumed to be the initial variant. In the next calculation variants the angle of the value of the involute profile angle was increased to 25° and 30°.

The analysed element is cylindrical gear wheel with a tooth line parallel to its axis, therefore calculations can be conducted using two-dimensional models. The calculation model is the cross section of the gear, perpendicular to its axis, created in the middle of the width of the toothed rim. Due to this limitation of geometry, the problem analysed can be defined as a flat stress state (Rusiński, Czmochowski, Smolnicki, 2000). In subsequent calculation variants, only the tooth profiles were changed, the remaining dimensions of the gears were unchanged. For FEM calculations, it was assumed that: the width of gears is small in relation to its diameter, the external loads of gears are evenly distributed over their entire width and that they work only in the plane of a cross-section. The defined assumptions and procedures allow with sufficiently high accuracy to perform calculations of gears differing only in the profiles of the teeth. Calculations for all models were solved under the same fixation and load conditions for each model.

In the FEM calculations, it was assumed that the analysed models would be made of ABS plastic, just like the original gear. For this material, the basic properties were in accordance with the manufacturer's recommendations: Young module 2400 MPa, yield strength 90 MPa, Poisson number 0.4. This material was chosen, also because it is easy to select the technology for making such gears. In production conditions, wheels can be mass-produced by injection moulding, while maintaining constant quality parameters. This material also allows the manufacturing of functional gear models using rapid prototyping techniques. Wheels made by 3D printing can be prototypes for experimental research or be a cheap, and quick to manufacture, replacement for the original part.

Only fragments with seven teeth were used for the calculations in order to limit the calculation time. Models prepared in this way are enough to correctly simulate the meshing of several pairs of teeth. An example view of the computational model of a gear prepared for FEM calculations is shown in Fig. 4.

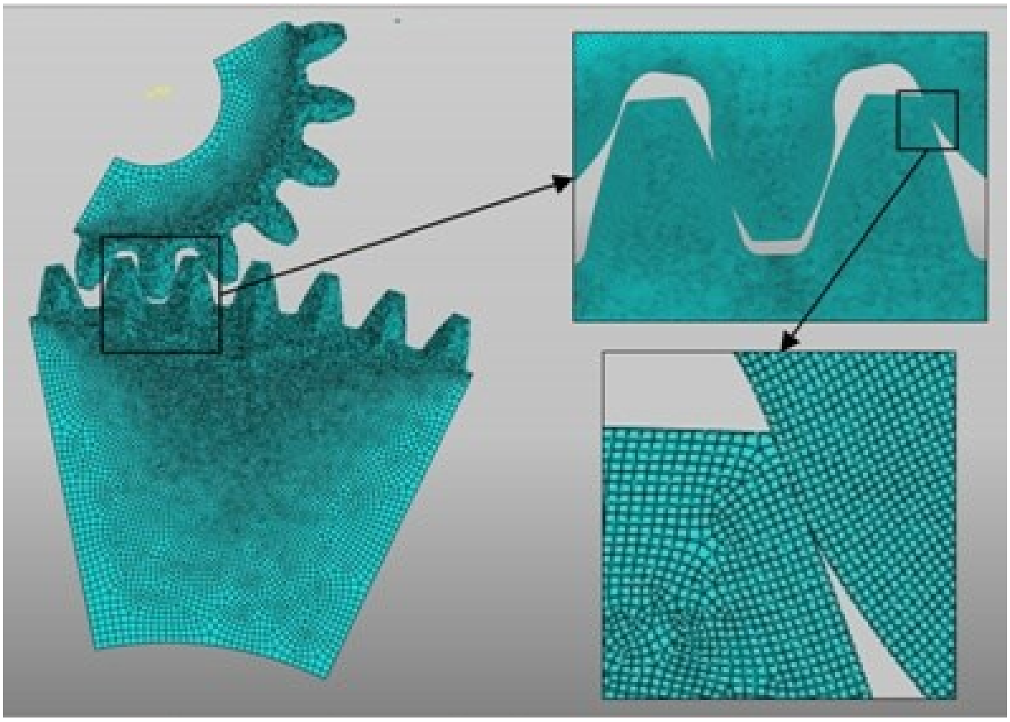

**Figure 4.** Gear calculation model prepared for FEM calculations in the Abaqus program.

In the defined computational model, the wheels could only rotate relative to their axis, defined by reference points (RP). The linking of models with their centre of rotation was realised by means of rigid links. For the transmission model, a forced rotation around its axis was performed at an angle of w = 0.5 rad. This allowed the cooperation of six pairs of teeth for each wheel to be traced. The gear load was realized by a torque amounting 4 Nm in the axis of the pinion model. Such a relatively low torque value was assumed because the analysis includes gears made of polymer plastic.

Due to the use of contact surfaces on the teeth, the real interaction of the wheels was simulated. The width of the gears analysed prepared for the calculations was 12 mm. The defined boundary conditions allow to obtain the required stiffness of the models and correctly determine the stresses in the tooth along the path of contact (Pacana, Kozik, Budzik, 2010; Wiktor, 2004).

The created flat model was discretised in the Abaqus preprocessor using finite quadrangular elements. The most precise division was defined on the toothed rims due to the expected high stress values in these areas. In the rest of the model, a much less dense mesh was specified, which is clearly visible in Figure 4. As a result of the division of the wheel, 87328 were obtained, while for the pinion 52169 finite elements.

## 4. Results of the analysis

The calculations allowed to obtain correct solutions for all prepared calculation models.

In all analysed models, higher stress values were located at the teeth contact of the both gears, and at the root of the tooth. Areas of increased bending stresses at the root of the tooth occur on the side opposite its load. This stress distribution is known from the literature and maximum stress values can be determined analytically based on ISO 6336-1:2006. Taking for calculations models with several teeth, it was possible to observe meshing conditions at various stages of tooth cooperation. This allows complete conclusions about the load on the teeth and the resulting stresses. It is possible to smoothly trace the cooperation of the teeth along the path of contact, both in a single-pair and two-pair contact.

Although a two-dimensional model was calculated, a high mesh density was used, so the accuracy of the obtained results was high. This allowed for precise processing of the results, and detailed analysis for all examined tooth profiles. They were compared to choose the most advantageous one for use in the reproduced model. It was observed that the lowest stress values were observed for an involute profile with 30° angle, and the highest for teeth with 20°. These differences are caused directly by the shape of the tooth, and especially its width at the root. For all three profiles, the single tooth begins cooperation at the same time, but the lengths of individual phases of cooperation (single and two-pair) are different for each of them.

The involute outline with 30° angle remains the shortest in the meshing of all the subjects, and has the longest duration of single-pair cooperation.

In the same way as for the reproduced gear, an analysis for the pinion model was conducted, but in this element it is not a problem and it is working correctly. For the pinion, the lowest values of bending stresses at the tooth root were also for the gears with a 30 ° angle of the tooth profile.

Qualitative analysis of various tooth profiles also concerned the determination of contact stresses on the flank of the tooth. Their maximum values occur in the area of contact between the teeth of the gear and the pinion. But this point during the meshing of the drive changes its position by moving along the path of contact. When reading the results of stresses on the flank of the tooth, in subsequent time steps of the calculations, the maximum values of contact stresses were sought. The stress distribution on the flank of the tooth always looked similar to Figure 5. An example of single-pair cooperation of involute gears with an angle of $\alpha = 30°$ is presented. On the horizontal axis, the length of the tooth flank is determined counting from the root to its apex, while on the vertical axis, the contact stress values are determined. The graph shows a very clear local increase in stress values, which corresponds to the place of single-pair cooperation of the tooth pair. With this method, the maximum contact stress values were read for all the calculation steps in order to compare the results for different tooth profiles. The graphs for all calculation models had a similar shape, but differed in the level of stress depending on the tooth profile used.

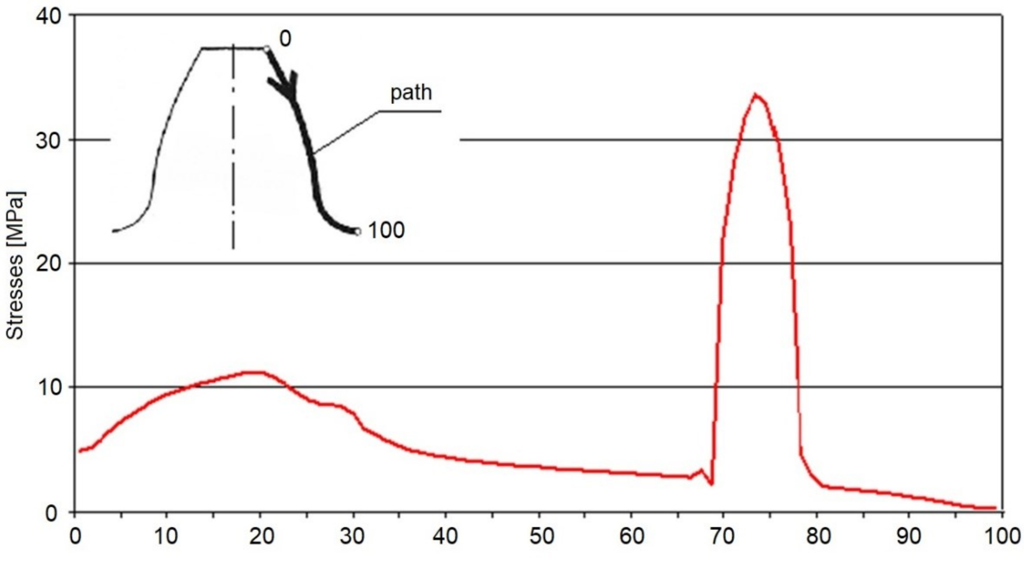


**Figure 5.** Method of reading the results on the flank of the pinion tooth.

Figure 6 shows the maximum contact stress values on the tooth surface for different profiles. The presented values are the maximum stresses recorded for each tooth faces for all anlysed profiles.

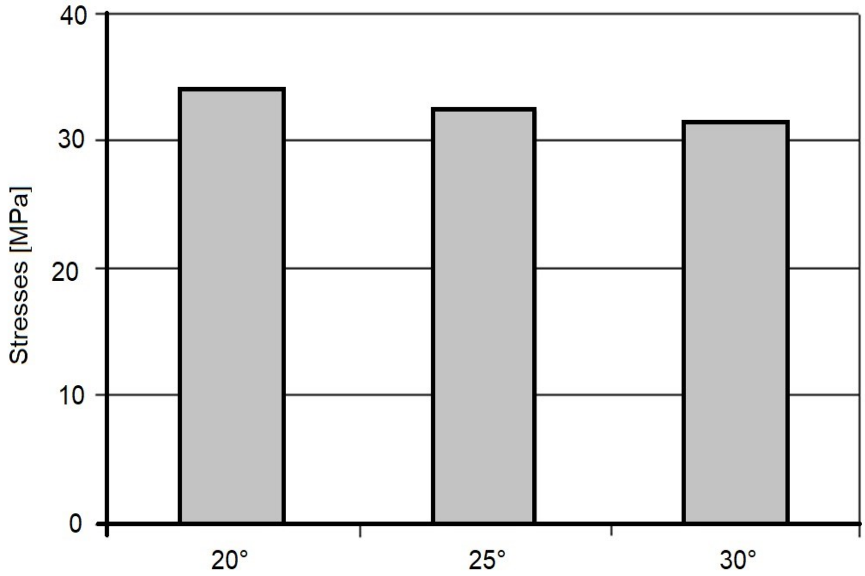


**Figure 6.** Contact stresses on the teeth surface of gears with different involute profiles.

In each of the calculation models, the maximum contact stress values were located at the end of the single-pair cooperation. The highest contact stresses were observed for models with a profile angle of 20° (36.34 MPa), while the lowest were observed for teeth with 30° angle of (35.67 MPa). The difference between the extreme values does not exceed a few percent, so it did not clearly indicate the benefits of using any of the design variants.

## 5. Fabrication of models

For three involute profiles, a reduction in the value of contact stresses was noticed as the angle of the profile increased. A similar trend occurred for the bending stresses at the root of the tooth, where the 30° profile also had the lowest stress values.

However, it should be noted that the choice of tooth profile should not always be determined only by maximum stress values. In this case, it should also be noted that as the angle of the tooth outline increases, it narrows at the apex, which can cause damage during work under load. The decision of the choice of the most advantageous solution in a specified situation should be made after a more in-depth analysis or on the basics of experimental research.

In the absence of other premises, it was assumed that the reconstructed gear will have a tooth outline $\alpha = 30°$, and the remaining parameters of the tooth rim will remain unchanged.

For this, the solid gear model was modified in the CAD program to the new geometry. The change in the its design consisted in removing the original toothed rim and replacing it with a new one generated in the CAD program, for the changed tooth profile. To better match the gear model to other assembly elements, the central hole in the hub was also made again.

Then, on the basics of solid CAD models, a physical model of the gear was made using the incremental method. To produce the prototype, the FDM (fused deposition modeling) method which consists of the layered construction of a model from molten polymer extruded from a heated nozzle. The material for the construction of the model was ABS in the form a filament, previously included in the FEM calculations.

The model preparation and the printing process were performed in the UpStudio program, and the printing was performed on the Up Box Plus printer (Fig. 9). Since the minimum available print layer thickness of 0.1 mm and the maximum fill density of the model were assumed, the printing process took a long time, over 5 hours.

After the printing process, it was still necessary to remove supports created only for the needs of the print itself and clean the resulting product. The physical model obtained in the 3D printing process is complete and fully functional, and also ready for assembly in the machine.

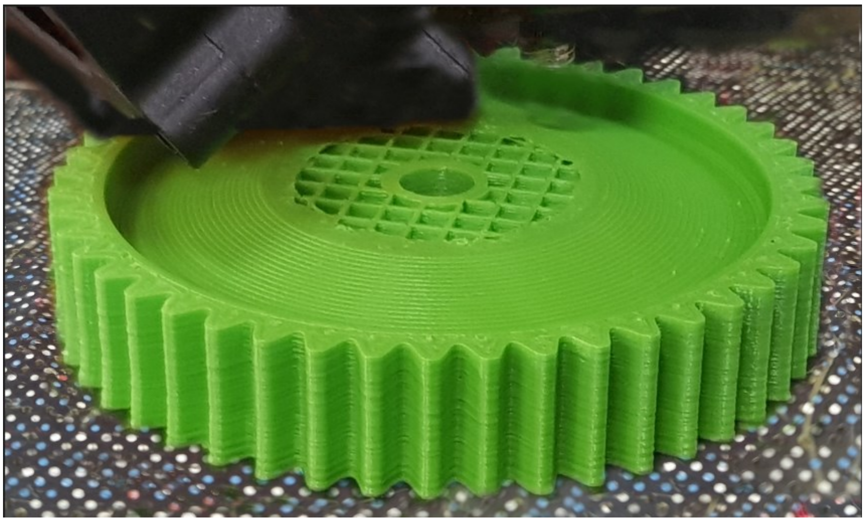

**Figure 7.** View of the gear during printing.

The correct work and durability of the gears are influenced not only by the parameters of the tooth rim, but also by their correct assembly. Therefore, the material and manufacturing technology was chosen, which allows for additional correction of geometry through machining. In this case, an additional reaming of the central hole was performed so that the gear wheel could be mounted on the shaft of the machine with precision and with the required clearance.

## 6. Summary

Reverse engineering allows us to make a copy of the original element while keeping its geometrical and strength parameters. In this article is presented how this process proceeded for the gear that is part of the drive of a meat mincer. The analysed gear was made of ABS polymer plastic, and was often damaged by breaking a single tooth. Since it was not possible to replace the damaged gear with a new one, reverse engineering methods were used to reconstruct it. The standard reproduction process was extended for an extra step involving the modification of the geometry for copied element. Changes in the design of the gear were aimed at improving its durability, and especially increasing the bending strength of the teeth. Therefore, the numerical model obtained as a result of contact measurements was subjected to numerical analysis using FEM. The calculations concerned different variants of gears that differed in the value of the profile angle of the involute tooth. Three angle values of 20°, 25° and 30° were tested. Preliminary evaluation of gears with different tooth profiles showed disparities in their load capacity. In none of the calculation variants, the determined level of bending stress values at the root of the tooth did not exceed the acceptable values, so they can be successfully used. The lowest stress values at the root of the tooth occurred for the profile angle $\alpha = 30°$. Also for this tooth profile, the lowest contact stress values occurred on the flank of the mating teeth. On the basis of these results, it was assumed that the original shape of the teeth with a profile angle of $\alpha = 20°$ will change into an involute with an angle of $\alpha = 30°$. After applying this modification, a copy of the gear was made using FDM 3D printing. So, the entire reverse engineering process of the gear was conducted, extended by its modification resulting from an additional numerical analysis of the FEM.

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