Double Flank Gear Roll Inspection of Spur Gears
Manufactured using Fused Deposition Modeling

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Abstract. The paper presents an experimental study that has as main objective the evaluation of the integration capacity of the spur gears obtained by FDM in high precision mechanisms. The development of precision mechanical systems required the use of the additive layer manufacturing technology in order to manufacture the gears that have specific particularities for the applications in which gears are integrated. Take these aspects into consideration, the paper presents the results achieved by testing on a ZWP-06 machine the gears obtained by fused deposition modeling technology. Gears were obtained on an Anet A2, semiprofessional 3D printer. To obtain a superior quality of toothed wheels, both process parameters: the material properties, and the features of the 3D printer were taken into account. The results, obtained from the test, revealed the level of influence of the execution parameters of the toothed wheels by FDM on their quality. The correlation of the process parameters remains the most important aspect for obtaining components with a high accuracy class, which complies with the resistance standards under the conditions of a shorter execution time.

1. Double flank gear roll inspection

The double flank gear roll inspection is a simple method to test the functional accuracy easily and quickly for spur gears \cite{1, 2}. The result is the sum of all given deviations. No matter which deviation the specimen has, the double flank gear roll inspection will detect it. The result of the double flank gear roll inspection is a summery error. That means, that it is not possible to determine the single errors causing the deviation. If the detected summary errors are within tolerance, it is assumed that also the single errors are within tolerance. If the deviation detected by the roll inspection is too big, the cause study is the operator’s job or the specimen has to be measured by a machine which is able to determine single deviations. The authors developed a research for different gears materials on a measuring setup for the double flank gear rolling inspection ZWP 06 from FRENCO. During the double flank gear rolling inspection two gears are rolled together free from backlash. ZWP 06, the double flank gear roll inspection machine, is specially designed for small high-precision gears. It is also suitable for plastic gears. The measuring force can be lowered to 0 N. The sophisticated design is extraordinarily precise and sensitive. The measuring carriage is supported free from backlash on four leaf springs \cite{3, 4}.

This so-called parallelogram suspension is very sensitive and registers even the smallest change in centre distance. The measurement process is motor driven by default. We used the FRENCO Software ‘FGI pro’. The sketch of the experimental setup is represented in figure 1. There are two gears: the master gear and the workpiece (specimen). The driver gear is the master gear. Master gear is
manufactured from steel.

Figure 1. Experimental setup ZWP 06

The software FGI pro includes both, the control of the drive and the evaluation of data. The software is in-house developed and programmed by developers for applications software. With the actual values being marked in colour, the specimen (workpiece) can quickly be evaluated as ‘Pass’ (green) or ‘Fail’ (red). Basically the software determines the following values:

- total radial composite deviation $F_i''$
- tooth-to-tooth radial composite deviation, $f_i''$;
- runout deviation by composite test, $F_r''$;
- short-wave component, $f_k''$.

2. Operating mode

Usually, gears transfer rotations and torques. Like all machine components, they are afflicted with production caused deviations. The challenge to produce a constant quality requires quick and easy inspection methods, which can be smoothly integrated in the production process. For a precise assessment of the gears’ operational behaviour, manufacturers make again use of the well tried double flank gear rolling inspection [2]. This method enables a quick assessment of gears in terms of total deviations.

It determines gear roll variations, tooth to tooth composite deviations, composite runout deviations and the short wave part and displays them clearly. Immediately after the measurement it can be seen whether the gear is acceptable or not. By the colouring the visual comparison of the actual values and the reference value is made easier. For each deviation there are used different colours, operator can easily observe the wrong deviations. The software creates a clearly laid out record showing (presented in figure 2):

Double flank rolling deviation $F_i''$

$F_i''$ is the difference between the maximum and minimum values of the working centre distance, $a''$, which occurs during a radial (double flank) composite test, when the product gear with its right and left flank simultaneously in tight mesh contact with those of a master gear, is rotated through one complete revolution. (DIN3960/3963)

Double flank rolling tooth to tooth deviation $f_i''$

$f_i''$ is the value of the tooth radial composite deviation corresponding to one pitch, $360^\circ/z$, during one complete cycle of engagement of all the product gear teeth ($z =$ number of gear teeth).

Radial Runout $F_r''$

$F_r''$ is the value of radial runout of the gear between the maximum and the minimum radial distance from the gear axis as observed by removing the short-term or undulation pitch deviations and analysing the long-term sinusoidal waveform.
3. Materials and methods for FDM technology

The process of rapid prototyping by FDM has developed spectacular, having as main advantage of obtaining robust parts with a relative low cost [5, 6]. However, a major disadvantage of this technology is represented by the accuracy and the roughness of the parts obtained.

Considering the advantages of rapid prototyping FDM, for the development of the specific control systems, at the global level there is a strong support through the open source applications type [5]. From this point of view, to assess the quality of the parts obtained by FDM there are a number of studies and research on the common software solutions and the properties of materials used [7, 8].

In the literature there are a number of researches which had as main objective optimize part surfaces obtained by FDM, addressing solutions that: application of a metallic paint on the surfaces of the printed, the application of any chemical treatments or post processing technologies of adjustment controls. These solutions have the main disadvantage to enter a new stage in the process of obtaining parts, stage which increases the time and cost of production.

Additional manufacturing processes are required for obtaining complex components in a short time, at a cost of production decreased. In order to fulfill these requirements, FDM process parameters must be established for each application [9]. The final quality is determined by the properties of the material, the parameters of the process and the characteristics of the machine [9, 10].

Researching the influence of the characteristics of the material on the quality of the components obtained by FDM there was used a 3D printer ANET A2, where the table movements run on X-Y axis, and the print head runs along the Z axis. System extruder material, using a system consisting of two gear-driven by a stepper motor. The printer has been calibrated resulting an accuracy of 0.1 mm for components which are simple forms.

The gears have been designed in SOLIDWORKS, and for obtaining the G-Code we used: v2.05 Repetier Cura Engine Slicer software. Materials characteristics are presented in table 1, for both materials: ABS and PLA.

| ITEM                  | ABS    | PLA     |
|----------------------|--------|---------|
| Density [kg/m³]      | 1.01   | 1.20-1.25 |
| Melt Point [C]       | 220-260| 190-220 |
| Melt Flow Index [g/10 min] | 1.43 | 7.8  |
| Tensile Yield Strength [MPa] | 40.96 | 62.63  |
| Elongation at Break [%] | 20.86 | 4.3  |
| Flexural Strength [MPa] | 45.44 | 65.02  |
| Flexural Modulus [MPa] | 1948.45 | 2504.4 |
| Impact Strength [MPa] | 22.11  | 4.28   |

Also, for both gears have been keep the same process parameters, being changed only temperature of the extruder and the temperature of the printer platform. In figure 3 there are presented the 3D printer (left) and the designed gear laying on the printing table (right).
4. Experimental results

There were considered three gears manufactured from steel, ABS1 and ABS2. All three gears have the same modulus, \( m = 1 \text{mm} \), number of teeth, \( z = 58 \), and the same thickness \( b = 12 \text{mm} \).

Steel gear was manufactured on a special gear cutting drill machine. Acrylonitrile Butadiene Styrene (ABS) is a 3D printing plastic and it was used for the yellow gear. It is a versatile petroleum-based material that belongs to a family of thermoplastic polymers. There are different brands and grades of ABS filament, which makes them unequal in terms of usage and design.

PLA is the most commonly used filament. It’s biodegradable, easy to print, and very strong material and was used for the black gear. The perfect choice for printing large objects thanks to its low thermal expansion (little to no warping) and for printing tiny parts because of its low melting temperature. All three gears (steel, ABS and PLA) are shown in figure 4. In figure 5 is presented the inspection of each gear on ZWP 06 machine. The results are presented in table 2.
|                | Linear chart | Polar chart |
|----------------|--------------|-------------|
| **Steel gear** | ![Image](image1) | ![Image](image2) |
| **ABS gear**   | ![Image](image3) | ![Image](image4) |
| **PLA gear**   | ![Image](image5) | ![Image](image6) |

**Figure 6** PLA Visualized Fourier spectrum
The Fournier spectrum of the measurement is displayed very clearly (figure 6). The frequency of the teeth is coloured. Beside that the software provides further features, like a comfortable filing, statistical evaluations, automatic detection of damages, measurement of tooth segments, qs-STAT port, etc.

5. Conclusions
The ABS and PLA gears were left in the environmental temperature in our laboratory and they were measured after three days from their manufacturing. For both printed gears we used the same fill factor of 20%.

The experimental results show that:
- The steel gear could be considered for Quality range = 4; (DIN3960/3963)
- The ABS gear could be considered for Quality range = 4; (DIN3960/3963)
- The PLA gear could be considered for Quality range = 5; (DIN3960/3963)

Considering steel gear and ABS gear we found that double flank rolling tooth to tooth deviation, $f''$, is better for ABS than steel gear. PLA gear is almost of the same quality like the steel gear (except double flank rolling tooth to tooth deviation $f''$).

The paper presents an experimental study that has as main objective the evaluation of the integration capacity of the spur gears obtained by FDM in high precision mechanisms.

The tests results reveal a superior precision of ABS gear in comparison with PLA gear.

A future research direction is represented by fatigue and strength tests of ABS gear wheel.

The authors developed several studies in order to evaluate the mechanical behavior of printed machine elements like: springs, gears, clutches, bearings, etc.

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