Experimental determination of plastic gear durability

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Abstract. There are many plastic materials (POM, PA66, PEEK, …) and material combinations available. The question is which combination is the correct one. It depends on many factors, like expected durability and price, means of production, e.g. injection moulding or cutting, lubrication, microstructure, fillers, etc. The available data bases and data sheets do not present conclusive results. So, it is of the utmost importance for a company to produce effective tests which could present correct results for each individual case.

The gear tooth flank profile could be also optimized. S-gear shape is characterized by a convex concave contact in meshing start and end areas. This implies improved properties in comparison to involute gears, like lower contact pressure, less sliding and lower frictional losses, stronger root and improved oil film when lubricated.

The paper presents some material properties for the combinations which were tested on the fatigue test benches, presents testing rigs, refers to experiments and discusses results.

1. Introduction
Plastic gears have become important alternatives to traditional metal gears in a wide variety of applications and their usage has expanded from simple low power motion transmission into demanding applications ranging from automotive, precision and medical equipment. Since designers push the limits of acceptable plastic gear applications, more is learned about the behaviour of plastics in gearing and how to take advantage of their unique characteristics. Plastic gears have lower weight and consequently lower inertia and run quieter than metal gears. They can run without external lubrication or their material can contain internal lubricants, e.g. silicone or PTFE. Their unit cost, based on manufacturing means, is lower than that of metal gears. They are corrosion resistant, depending on gear material and media. The most common materials are polyamide (PA) and polyacetal (POM). Due to harsher requirements, many new, high performance materials were developed. The use of fillers, reinforcements, internal lubricants, etc., became necessary, focusing on higher strength, wear and heat resistance. However, metallic materials data were systematically collected over decades, whereas there is apparent a lack of data (e.g. load carrying, wear performance, etc.) in the case of plastic materials, which coincides with rapid development of new materials. Various companies produce similar materials with similar properties as well. Proper combination of materials can result in long and reliable operation of such mechanisms and a cost-effective solution.

Despite the same basic material and similar fillers, materials disclose dissimilar mechanical and thermal behaviour. So, it becomes important for the gear producing company to have efficient means of testing and an effective database to use optimal solutions for each design task. Beside two old testing benches a new one was developed to facilitate testing according to the VDI 2736-4 [1], which is also important in the context of data inclusion in the KissSoft [2], which is a gear design software.
Some actual material combinations of gears, which can be used in complex parts are presented in the following chapter. It was discovered that the tooth flank shape has influence on gear efficiency. Some tests with small plastic gears conducted to assess Wöhler curves for gears with various material combinations and long-term tests with smaller loads to run up to 10 or 20 million cycles in the controlled environment have been conducted recently [3-6]. Results comparing S- and E-gear shape indicate better performance of S-gears. S-gear geometry feature lower contact pressure, less sliding and frictional losses, stronger root and improved oil film when lubricated.

Some accomplished experimental results (i.e. fatigue tests) with gears made of various material combinations are presented and discussed as well.

2. Material properties

Two series of tests were conducted: POM – PA66 and Steel C45 – PA66. POM and C45 gears were used as driving gears and PA66 as driven gear. Regarding PA66, four materials with different fillers were used. Basic properties of these materials are collected in Table 1. Some data are missing since they are not available on the corresponding data sheets.

| Property                          | generic PA66 | LUBRICOMP RFP36 | Zytel 103HSL NC010 | Promyde B30 P2 GB30 | Luvocom 1/GF/30/TF/15/SI/2-2 |
|----------------------------------|--------------|-----------------|-------------------|---------------------|----------------------------|
| Additional description           |              | 30% glass fibres + PTFE + silicone lubricated | 30% glass spheres | 30% glass fibres + 15% PTFE + silicone heat stabilized |
| Density                          | \( \rho \) [g/cm\(^3\)] | 1.13 ... 1.16 | 1.46 | 1.14 | 1.36 | 1.48 |
| Modulus of elasticity (tensile)  | \( E \) [MPa] | 3000 | 3100 | 4400 (dry) | 9900 |
| Tensile strength                 | \( R_m \) [MPa] | 85 | 148 | 60 | 180 |
| Tensile strength at yield        | \( R_p \) [MPa] | 85 | 148 | 60 | 180 |
| Elongation at yield / break      | \( \delta \) [%] | 5 | 4.5 | -8 | 3.5 |
| Poisson's ratio                  | \( \nu \) [-] | 0.4 | | | |
| Service temperature (short term) | \( T_m \) [°C] | 140 ... 170 | | | 160 |
| Service temperature (long term)  | \( T_{op} \) [°C] | 80 ... 100 | | | 110 |
| Thermal expansion coeff. (CLTE)  | \( \alpha \) [K\(^{-1}\)] | 4 x 10\(^{-5}\), 2.5 x 10\(^{-5}\), 11 x 10\(^{-5}\) | 11 x 10\(^{-5}\), 2 x 10\(^{-5}\), 6 x 10\(^{-5}\), 2 x 10\(^{-5}\) |
| Friction coefficient             | \( \mu \) [-] | 0.96 / 0.48 | 0.25 | 0.12 / 0.14 |
| Thermal conductivity             | \( \lambda \) [W/(mK)] | 0.23 | 0.25 | 0.24 |
| Specific heat                    | \( c \) [J/(gK)] | 0.06 | | | |
| Thermal diffusivity              | \( \chi \) [mm\(^2\)/s] | | | | |

1 - generic PA66 - VDI 2736, Blatt 1 [7]
2 - Lubricomp RFP36 - Sabic [8]
3 - Zytel 103HSL NC010 - DuPont [9]
4 - Promyde B30 P2 GB30 - Nurel [10]
5 - Luvocom 1/GF/30/TF/15/SI/2-2 - Lehman&Voss&Co. [11]

According to the datasheet [8] is Lubricomp RFP36 distinguished by improved strength due to glass fibres and better frictional properties. DuPont’s Zytel 103HSL NC010 is a basic PA66 with added lubricant and features high mechanical strength, excellent balance of stiffness and toughness, good high temperature performance, good electrical and flammability properties, good abrasion and chemical resistance [9]. Promyde B30 P2 GB30 is distinguished by high mechanical strength, hardness, rigidity, thermo stability (melting point 220°C), and resistance to hot lubricants and water. Parts made of this material have particularly high dimensional stability and creep strength [10]. Luvocom 1/GF/30/TF/15/SI/2-2 is characterized by improved sliding and wear behaviour and is self-lubricating.
It is meant for precision parts with high dimensional stability, high heat resistance and with tight tolerances [11]. POM used in these experiments is Lubricomp KA000M, which is a copolymer containing aramide fibres and a proprietary lubricant. Available data contain density of 1,36 g/cm³, E=2600 MPa, Rm=41 MPa and friction coefficient of 0,21 [12].

Properties of various fillers (fibres, stabilizers, lubricants, etc.) are collected in Table 2. These fillers influence mechanical, tribological, electrical, technological, thermal and chemical properties of basic materials.

| Table 2. Properties of fillers and reinforcing materials [13]. |
|---------------------------------------------------------------|
| Filler            | Positive influence                                      | Negative influence                             |
| glass, carbon or  | increase in stiffness, tensile strength, flexural fatigue| reduction in impact strength                   |
| aramide fibres    | strength and heat distortion resistance                 |                                               |
| glass spheres     | Improved processability, low, uniform shrinkage, low    |                                               |
|                   | warpage, close tolerances, better surface finish, isotropic |
|                   | distribution of stress and deformation, etc.            |                                               |
| PTFE              | reduction in friction and wear                          | reduction in impact strength and flexural fatigue strength |
| PE                | reduction in friction                                    | reduction in impact strength                   |
| graphite, boron   | reduction in friction and wear, increase in thermal      | reduction in impact strength                   |
| nitride           | conductivity                                            |                                               |
| silicone oil      | reduction in friction and wear, increase in toughness   | /                                              |
| mineral fillers   | increase in heat distortion resistance                  | /                                              |

3. Testing appliances

3.1. Small testing rigs for durability testing

Testing results presented in this paper are based on two small testing rigs were used to acquire gear durability data. Small gears (m = 1 mm, z₁ = z₂ = 20, b = 6 mm, with involute or S tooth flank shape) of varying material combinations (thermoplastic/thermoplastic or steel/thermoplastic) were exposed to a constant torque and driving speed and run until failure. In this way Wöhler curves are obtained. The testing rig is illustrated in Fig. 1. It consists of a framework on which two asynchronous squirrel cage electro-motors with 4 poles are mounted. On the motor rear side there are two fans to remove redundant heat. Two small gears are mounted in such a way to adapt centre distance. Power transmission from the motors to the shafts is by belts. Motor speed is governed by a frequency inverter. In this way load is implemented by a speed difference. It is important to have possibility of measuring contact temperature by a thermal camera, so the testing device was designed in such a way to enable frontal view. Motor power is 0,37 kW with synchronous speed of 1500 rpm. Maximal torque is 1,8 Nm.

3.2. Testing rig for tests according to VDI

While small gears are not demanding regarding production cost and are modest in operating power requirements, the new VDI Richtlinie 2736, Blatt 4 [1], prescribed some other gear sizes, depending on production means. Therefore, it was decided to produce a new testing rig. Two goals are 1) to produce tests comparable to a broader professional community and 2) to discover proper correction factors for tests with small testing rigs.

Special purpose testbench is developed and designed for testing the cylindrical spur or helical gear sets in accordance with [1], both »Size 01« or »Size 02«, or customer specific for a company’s special purposes. The testbench is designed for either steel-polymer or polymer-polymer gear set. The device is represented in Fig. 2 schematically (left), the user interface of the control unit (right top) and size 01 meshing gears (right bottom).
The testbench consist of two squirrel cage asynchronous motors (M1, M2) driven by frequency converters (FC1, FC2) with an internal PLC controlling the testbench operating parameters (load and speed). Further, the testbench is equipped with the thermo-camera providing the relevant information of the temperature distribution of the gear set being tested. The camera may be installed in a perpendicular direction to the gear meshing plane (shaft axis), with an observation point directly on the tooth flanks or it may be positioned to observe the gear face with a small inclination angle regarding the shaft axes orientation. The camera acquires spot temperature to the PLC, while the thermal images are sent to the PC periodically. The Optris Xi 400 device is used with automatic zooming, hot spot finder, IR sensor resolution of 382x288 points and frequency of 80 Hz.

The operating principle of the testbench is based on the operating characteristics of the squirrel cage asynchronous motors, driven by the frequency converter. The target speed of the primary gear is set, from which the excitation frequencies of both motors, considering gear ratios, are calculated (not necessary having the same value) by the PLC itself. After gear speed is reached the load is applied by altering the excitation frequency of the driven motor, hence the slip and consequently the load on both motor changes. The actual load transmitted through the gear set is evaluated with the pre-calibrated lookup tables. Once the failure of the gear set is detected, the testbench stops automatically. Since the counting of the load cycle is, beside the load level, an essential information, it is provided by the testbench PLC.

All relevant data i.e. the evaluated load, speed, temperature and the load cycle are stored in an internal PC in a digital form throughout the test-run.
3.3. Gears
Manufacturing means of plastic gears can be injection moulding or cutting. Cut gears are of industrial interest for smaller lots and when a more precise tooth flank shape is prescribed or if alternative gear tooth flanks are of interest. Comparing cut and moulded gears of the same module and number of teeth by measurements of the quality Q according to DIN 3961 or DIN 3962 discloses at least for two grades higher Q of cut gears. Measuring gears on Wenzel GearTec coordinate measurement machine in our case showed Q=9 and Q=11 for cut and moulded gears, respectively [3].

Regarding our experience with moulded and cut gears it was decided that basic disks of plastic materials of interest are injection moulded, using an axial sprue enabling higher material flow to gain quality uniform physical characteristics and evenly distributed fillers (when applicable). Disks are then cut by a HSS cutting hob on the CNC Koepfer machine tool as to enable effective manufacturing. As already stated, gears with m=1.0 mm, z_1=z_2=20, b=6.0 mm are in use in small testing rigs. The initial pressure angle of the S-gears \( \alpha_{w0}=18^\circ \) and \( \alpha_p=1.5 \), whereas standard pressure angle \( \alpha_w=20^\circ \) is used for E-gears.

Gears planned for the new testing rig are (according to VDI 2736, Blatt 4):

a) size 1: \( m_n=1 \) mm, \( z_1=17 \), \( z_2=39 \), \( b_1=8 \) mm, \( b_2=6 \) mm;

b) size 2: \( m_n=2 \) mm, \( z_1=30 \), \( z_2=30 \), \( b_1=13 \) mm, \( b_2=12 \) mm;

c) custom gear combinations.

4. Important properties of S-gears
Several papers have been written clarifying the idea of S-gears in detail [13-16]. Some essential properties are summarized in this chapter. S gears feature a convex-concave contact in the meshing start and end areas, which can be achieved by a progressively curved path of contact, which is half symmetric. So, the generating rack profile (cutting tool) is defined in a following way:
\[ y_p = a_p (1 - (1 - x_p)^n) \]  

This parabolic type function defines the upper part of the rack profile whereas its counterpart is derived as a half-symmetric function. The unit of measurement is the module m. And \( a_p \) as a height factor and \( n \) as curvature exponent define a rack flank shape. \( y_p \) and \( x_p \) are the rack flank coordinates with the origin in the kinematic pole C. Such a rack profile defines a unique path of contact and out of there gears with any number of teeth can be derived with a bijective transformation.

The most important features of S-gears regarding plastic materials are summarized below:
- A tooth flank shape is optimized by a height factor \( a_p \) and exponent \( n \), which enable gear tooth design according to prescribed properties. So, one can define a stronger tooth root, a longer convex-concave area, a curvature of the path of contact, a lower starting pressure angle in C, etc.
- Spur S-gears can operate with a low number of teeth, even as small as 6 or 4.
- S-gears feature convex-concave contact near meshing start and meshing end. This infers higher reduced radii of curvature and results in lower contact pressure.
- S-gears feature relatively longer dedendum part of a tooth flank (comparing to the involute gears). This implies sliding of a contacting pinion dedendum and gear addendum which results in less frictional work and lower temperature [15], which is illustrated in Fig. 3.

![Figure 3](image)

**Figure 3.** Contact density – the length of sliding of the gear addendum on the pinion dedendum.

The dedendum-addendum size difference depends on module, number of teeth, pressure angle. For S-gears the said difference also depends on forming factors – the height and the exponent. The size difference in the case of S-gears is comparatively more convenient, so less sliding is produced along the contact propagation compared to the involute case. Figure 1 (detail H) also shows the dedendum and the corresponding addendum of the E-gear. The starting pressure angle for the S-gear pair is 22° and that of the E-gear pair 20°. The contacting addendum flank length of the latter (for the case in Fig.3) is about twice as large as that of the pinion. And the obvious difference between E- and S-gears means more sliding and thermal impact in the case of E-gears.

5. Experimental results and discussion
Past research showed a clear distinction between S- and E-gear geometry in favour of former, which can be attributed to the mentioned features of the S-gears [3-6]. Two types of experiments were conducted:
a) durability tests where gears made of POM (driving) and PA66 (driven) run up to failure and tests where both gears were made of POM;
b) long term tests up to about 20 million cycles.

The rotational frequency (app. 1350 min\(^{-1}\)) and torque (from 1 up to 1.6 Nm) were set at experiment start. Tests were run at room climate circumstances. Tests confirmed theoretical assumptions. However, long term tests (1350 min\(^{-1}\) and 0.6 – 0.7 Nm) were time consuming and conducted in circumstances where ambient temperature varied to high extent, so additional tests in more stable environment should be arranged.

Current experimental work with small E-gears \((m = 1 \text{ mm}, z = 20, b = 6 \text{ mm}, \alpha_w = 20^\circ)\) was conducted at room temperature 22 ± 0.5 °C. Input speed was 1400 min\(^{-1}\) and chosen torques were 1.1; 1.3 and 1.5 Nm. Each experiment was repeated 3 times to acquire statistical evaluation. The basic goal was to explore and evaluate the influence of the chosen material combination on attained number of cycles and heat flow and temperature rise in the gear meshing zone. S-gear experiments are already planned.

1. a C45R steel gear was driving and gears of various PA polyamides, basic and with reinforcements in the first experimental cycle.
2. The same PA driven gears and a POM with with fillers were used in the second experimental cycle. The corresponding material data are collected in Table 1.

**Figure 4.** Temperature rise during durability testing of material combinations C45R – PA \((n = 1400 \text{ min}^{-1}, T_{\text{ok}} = 22^\circ\text{C})\) \(T = 1.5 \text{ Nm (top left),}\ T = 1.3 \text{ Nm (top right),}\ T = 1.1 \text{ Nm (bottom)}\)

Colours: Zytel – green, Luvocom – blue, Lubricomp – orange, Promyde – grey)

Figure 4 shows temperature time diagrams for the gear pairs C45R/PA. Following conclusions can be derived based on these results:
- The best performance, the highest number of cycles \(N\), was accomplished by Zytel 103 HSL NC010 made of basic polyamide 66 (PA 66), heat stabilized.
- The highest accomplished spot temperatures \(T\) were developed during meshing of gear combination C45R / Zytel 103 HSL NC010.
Table 3 collects average spot temperatures in a stable range for each polyamide, whereas Fig. 5 shows thermal camera snap-shots for the meshing C45R/Zytel 103 HSL NC010 gear pairs loaded with torques 1.5, 1.3 and 1.1 Nm, respectively in a temperature stable region.

The highest temperatures in the meshing zone appear with gears made of Zytel 103 HSL NC010, which is expected, since this polyamide is non-reinforced, but heat stabilized, so it contains additives to improve properties at higher working temperatures. The combinations of working gear pairs C45R/Lubricomp RFP36 and C45R/Luvocom 1/GF/30/TF/15/SI/2-2 show the lowest temperature, which is also stable almost until gear breakage. This can be attributed to the presence of PTFE in both polymers. PTFE lowers friction in the contact and consequently lower temperatures are developed in the meshing zone. A more significant temperature drop with lower load was detected with gears of Zytel 103 HSL NC010 and Promyde-a B30 P2 GB30. These materials do not contain Teflon, which confirms conclusions for materials containing PTFE.

Table 3. Average spot temperatures in a stable range during testing (steel/PA).

| Torque M [Nm] | 1.5 | 1.3 | 1.1 |
|---------------|-----|-----|-----|
| Thermoplast   |     |     |     |
| Zytel 103 HSI NC010 | 100 | 83  | 60  |
| Lubricomp RFP 36 | 48  | 45  | 44  |
| Promyde B30 P2 GB30 | 80  | 68  | 47  |
| Luvocom 1/GF/30/TF/15/SI/2-2 | 50  | 53  | 48  |

Figure 5. Thermal camera snap-shots for the meshing C45R/Zytel gear pairs in a stable region $T=1.5$ Nm (left); $T=1.3$ Nm (centre); $T=1.1$ Nm (right).

Table 4. Time/No. of cycles and range for various loads and material combinations (steel/PA).

| Torque M [Nm] | 1.5 | 1.3 | 1.1 |
|---------------|-----|-----|-----|
| Thermoplast   |     |     |     |
| Zytel 103 HSI NC010 | 115966 | 248085 | 354968 |
| Lubricomp RFP 36 | 28225 | 105027 | 231828 |
| Promyde B30 P2 GB30 | 26341 | 124527 | 308844 |
| Luvocom 1/GF/30/TF/15/SI/2-2 | 42171 | 111165 | 179873 |

Table 4 shows how many cycles $N$ were accomplished in tests with steel/polyamide gear pairs until breakage for loads 1.5, 1.3 and 1.1 Nm. Gears made of Zytel were the most durable, so their $N$ values were put to 100% for comparison with other materials.

Table 4 reveals that the gear pair combination C45R/Zytel 103 HSL NC010 is the most durable, which can be attributed to the improved heat stabilized basic material and its deformability regarding stress state developed during meshing with the steel driving gear. Material combinations steel/PA with glass fibres have a negative influence on the thermoplastic material structure. One can say the glass fibres increase brittleness and, in this way increase a probability of breakage in dynamic fatigue of the used thermoplastic. Materials with glass spheres exhibit the same effect to a lower degree.
Fig. 6 shows temperature time diagrams of the second cycle of experiments. So, POM was used for a driving gear and PA for driven gear. POM in this case was Sabic’s Lubricomp KA000M, which contains aramid fibres. PA materials are the same as in the first cycle, with the exception of Promyde.

Figure 6. Temperature rise during durability testing of material combinations POM – PA ($n = 1400 \text{ min}^{-1}$, $T_{ak} = 22^\circ\text{C}$) $T = 1,5 \text{ Nm}$ (top left), $T = 1,3 \text{ Nm}$ (top right), $T = 1,1 \text{ Nm}$ (bottom) Colours: Zytel – green, Luvocom – blue, Lubricomp – orange).

Table 5. Average spot temperatures in a stable range during testing (POM/PA).

| Torque $M$ [Nm] | 1,5 | 1,3 | 1,1 |
|-----------------|-----|-----|-----|
| Thermoplast     |     |     |     |
| Lubricomp RFP 36| 70  | 61  | 58  |
| Zytel 103 HSI NC010 | 59  | 48  | 48  |
| Luvocom 1/GF/30/TF/15/SI/2-2 | 66  | 62  | 55  |

Table 6. Time/No. of cycles and range for various loads and material combinations (POM/PA).

| Torque $M$ [Nm] | 1,5 | 1,3 | 1,1 |
|-----------------|-----|-----|-----|
| Thermoplast     |     |     |     |
| Lubricomp RFP 36| 38093 | 100 | 81067 | 100 | 252939 | 100 |
| Zytel 103 HSI NC010 | 34911 | 92  | 73892 | 91  | 326300 | 129 |
| Luvocom 1/GF/30/TF/15/SI/2-2 | 8053 | 21  | 29022 | 36  | 142004 | 56  |

The best performance in this case can be attributed to combinations Lubricomp KA000M (POM)/Lubricomp RFP 36 (PA66) and Lubricomp KA000M (POM)/Zytel 103 HSL NC010. Lubricomp performs slightly better at higher loads and Zytel with lower loads. So, one could expect better performance of Zytel gears with loads at fatigue strength level, which is due to stable mechanical properties of this material at increased temperatures.

Table 5 collects average contact spot temperatures in a stable region for mating POM/PA gears. Zytel 103 HSL NC010 develops the lowest temperatures in the stable range among all materials. Both other
materials contain glass fibres and PTFE and it appears that the temperatures in these cases are higher. Regarding temperature range (heat development) and durability (No. of cycles, Table 6) the basic, heat stabilized PA66, Zytel 103 HSL NC010, appears to be the most appropriate.

6. Conclusion

New plastic materials emerge all the time. Improved POM and PA66 were used in this paper. So, their mechanical and thermal properties were presented here. Regarding manufacturing raw parts were injected and gear cut subsequently. Despite net shape injected parts are preferred due to their price in mass production, cutting with professional hobs is necessary when gears of higher quality are required. Hob cutting is also more productive method.

Despite small testing rigs are quite effective for small gears, the new VDI Richtlinie, Blatt 4 [1] requires some other gear sizes, so a new testing rig was manufactured. The basic idea is, to produce tests, which can be directly compared to other. Some test cycles on the new testing are already in progress. Tests in this paper were conducted entirely on the small devices with small involute gears. A hob cutter for S-gears was already manufactured and tests are in plan later this year. S-gears are of interest due to lower frictional power comparing to E-gears.

In this paper presented test results show some interesting differences between different mating gears material combinations. It appeared that Zytel 103 HSL NC010, basic, heat stabilized PA66 serves the best as a driven gear with both driving gears, namely steel C45R and Lubricomp KA000M, aramid reinforced POM. This is true for material selection presented here.

Tasks which are in focus are S-gears experiments and adaptation of the results based on small testing rigs to the newer VDI based results.

Basic aim of performing durability tests of thermoplastic gears according to the VDI 2736, Blatt 4 is exportation of acquired temperature data (tooth flank and root) and number of cycles of tested gear pair at gear failure into the program system KISSsoft. Based on the input gear geometry, material properties, working conditions and data acquired from tests Wöhler curves are produced program aided for a chosen (tested) material and gear combination for prescribed operating temperatures.

Acknowledgment

The investment is co-financed by the Republic of Slovenia and the European Union under the European Regional Development Fund, no. SME 2/17-3/2017 and C3330-18-952014

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