Szent István University

TRIBOLOGY RESEARCH OF ENGINEERING PLASTICS/STEEL FRICTION PAIRS

- friction of polymer/steel gears -

Ph.D. thesis

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CONTENT

1. INTRODUCTION

During operation of different machines large variety of failure process can occur. Dominant reason of the breakdowns is origined from the movements of machine elements that are subjected to friction. Friction generally results different wear mechanism and different form of wear. For correct and suitable use of those machine elements, it is necessary to know all their material properties. Nowadays designing for strength goes quite well, for life period and fatigue reasonably, but the tribological behaviour is not known in depth. There is a lack of good catalogue information and literature data, complicating the design and dimensioning of such a systems. Engineers in many fields frequently require estimates of the magnitudes of the friction and wear likely to be experienced by different combinations of materials sliding or rolling together in various environments.

Regarding the sliding pairs we can meet more often engineering polymers as replacement of conventional steels having advantageous tribological properties in general. Along with the new industrial applications there has been development of new materials, coatings, composites, which need tribological properties to be discovered. Following this idea in my research program I decided to clarify the exact friction behaviour of engineering polymer/steel friction pairs focusing finally on plastic/steel gear pairs.

I approached the tribological problem on the basis of system theory introduced by Czichos. First I studied the literature of involute gear pairs and gear mesh with conventional materials and I paid special attention to new engineering polymers applied in gear systems. As a result I clarified the load and speed condition with some potential materials of gears to be tested. I designed the following tribology test systems:

1. Small-scale plastic specimens. Conventional pin-on-disc tribometer was used to obtain basic friction and wear data (plastic pin and steel disc). I designed a further method of dynamic modelling as well, with small-scale specimens having dynamic load and speed effects, just like between gear teeth profiles.
2. Large-scale plastic specimens. Tribological research on modern self-lubricating materials is generally performed by means of small-scale specimens, because of the lower costs and the flexibility of testing. The results of these small-scale tests, however, can not easily be extrapolated to real (large) constructions. Some of the reasons are: misalignment, edge effects, material inhomogenity, features as wear particle grooves or anti-creep devices. Thus, large-scale (real-scale) specimen tribotesting was needed with dynamic conditions to have better approach to gear friction and to have more global tribological information about the selected material pairs.
3. Real machine element tribotesting. I designed a new method to measure the friction during gear mesh along the action line of involute gear profiles. Formerly there were no data about this phenomenon just calculated values (forces and torque) concerning constant friction coefficients. In my new tribotesting system I clarified the real friction process along the action line in the function of sliding distance (running time of gear drive).

With these test methods I carried out large number of tests about friction, wear and friction heat generation. Finally my focus went on friction concerning the present role of plastic/steel gear drives due to unlubricated applications. The obtained test result let me compare the different test systems and clarify the correlation between friction result of small-scale-, dynamic-, large-scale and real gear friction results. My conclusions about correlations of the test system are put into tables in the dissertation.

2. MATERIAL, METHOD, RESULTS

2.1. Place of tribotests

Small-scale tribotesting with engineering plastic samples were carried out at the Institute for Mechanical Engineering Technology, Faculty of Mechanical Engineering, University Gödöllő, Hungary. These tests were: static condition „pin-on-disc”, dynamic condition „pin-on-plate” and real gear teeth connection. The main target of those was to clarify the basic friction and wear behaviour different material pairs under various conditions and to study the role of dynamic effects in load and speed.

Large-scale tribotests were carried out at Laboratory Soete, University Gent, Belgium. The role of those measurements was to study the friction and wear processes in the function of strongly differing dimensions of the tested samples.

2.2. The tested materials

Table 1 presents the tested polymers. For the measurements semi-finished engineering plastic products (cast or extruded rods and plates) were used in all cases as starting base material. From the semi-finished products I produced the small and large-scale samples as well as the gear samples by machining.

Table 1. Materials used for tests

Brand name*	**Name**	**Shortened name**
DOCAMID 6G	cast polyamide 6, natrium	PA 6G Na
DOCAMID 6G H	öntött poliamid 6, magnezium	PA 6G Mg
DOCAMID 66 GF30	extruded polyamide 66 + GF	PA 66 GF30
DOCACETAL C	Polyacetal	POM C
DOCAPET TF	Polyethilene-terephtalate + PTFE	PETP /PTFE
DOCALIT	Clothe-base phenolic	Bakelite

* www.quattroplast.hu

2.3. Measurements with small-scale specimens

The main objective of the measurement is the determination of the sliding friction characteristics of the selected polymer samples on a ground steel surface. At first, I performed the laboratory model tests in traditional pin-on-disc systems. On the basis of the unidirectional sliding friction and the surface load arising from the contact along the surface, the friction and wear characteristics of the polymers can be properly ranked and the effects of additives are well recognizable. In practice, the majority of parts are subjected to dynamic effects. For testing the effects of dynamic stress on friction, I programmed a dynamic motion path on which the plastic sample was supposed to travel at a variable speed and in the meantime, the load amount was to vary, as well. Thus, the effects of static and dynamic stress can be analyzed in the friction and wear behavior of polymers.

In the course of the tests, I determined the friction coefficient values related to static and dynamic stress conditions. Table 2 depicts the differences between the dominant conditions of the measurement systems.

Upon the static condition pin-on-disc and the dynamic condition pin-on-plate tests, the dimensions of the cylindrical samples are as follows: diameter Ø6 mm, length 15 mm.

In the case of small-scale plastic sample measurement, the material of the countersurface is S 355 structural steel, in a ground state. The elasticity modulus is E=210 GPa. The diameter of the steel disk is 350 mm, the thickness is 13 mm.

Table 2. Categories of test systems

	Category I. „static" pin-on-disc	**Category II.** „static" pin-on-disc	**Category III.** „dynamic" pin-on-plate
Surface roughness of the mating steel [μm]		R_a 0,05 – 0,15 R_z 0,31 – 0,93	
Normal load [MPa]	2	5	1 - 12
Sliding speed [m/s]	0,4	0,4	0,02–0,025–0,3–0,35-0,4
Ambient temperature [ºC]		23	
Sliding distance [m]	1000	1000	5 cycles on the path

The summary of the results are put into table 3.

When testing polymer/steel material pairs on small-scale samples, the following can be established:

- In the case of textile Bakelite, friction and friction heating are unfavorably high, wear resistance is weak. In the running-in phase, the polymer-film and dynamic equilibrium develop at a smaller pace.

- In the case of PETP/PTFE, a favorable (low) friction and friction heat can be experienced, which is also accompanied by good wear resistance. It is not sensitive to dynamic effects, the running-in process and the development of a friction equilibrium are smooth and even.

- In the case of polyamides, the effects of different mechanical characteristics can be partly recognized in the tribological behavior. The greater stiffness (PA 6G Mg) has a negative effect on even friction but not on wear. Running-in is faster. The higher rigidity, elasticity modulus, smaller impact strength (e. g. glass fiber reinforcement) render the material less sensitive against dynamic stress effects. An exception from this is the natural cast Polyamide 6 with Na catalysis, which resulted in a higher degree of wear in the dynamic system.

- POM C has a favorable friction characteristics, but its wear resistance is weak in comparison with the other thermoplastics. Running-in as well as the development of dynamic equilibrium (adhesion, re-adhesion) are favorable, similar to the PETP/PTFE composite.

Table 3. Summary of test results with small-scale plastic specimens

	Materials	**Friction ranking**	**Coefficient of friction**		**Change of near-contact temperature**		**Wear + deformation**	
			μ_{tmax}	μ_{davr}	ΔT [ºC]		Δk [mm]	
Category I.	**PETP /PTFE**	1	0,209	0,205	3,79		0,00346	
	POM C	2	0,218	0,218	4,77		0,01026	
	PA 66 GF30	3	0,313	0,26*	5,4		0,0082	
	PA 6G Na	4	0,300	0,279	4,04		0,00836	
	PA 6G Mg	5	0,365	0,288	4,37		0,0108	
	Bakelite	6	0,519	0,36*	8,96		0,01518	
			μ_{tmax}	μ_{davr}	ΔT [ºC]		Δk [mm]	
Category II.	**PETP /PTFE**	1	0,184	0,176	4,24		0,00692	
	POM C	2	0,203	0,203	4,84		0,01556	
	PA 66 GF30	3	0,255	0,212	5,41		0,00882	
	PA 6G Na	4	0,295	0,234	4,49		0,01236	
	PA 6G Mg	5	0,325	0,249	5,41		0,0157	
	Bakelite	6	0,755	0,55*	22,7		0,03946	
			Cycle 1.	**Whole path run**	**Cycle 1.**	**Whole path run**	**Cycle 1.**	**Whole path run**
			μ_{1avr}	μ_{5avr}	ΔT [ºC]		Δk [mm]	
Category III.	**Bakelite**	1	0,065	0,078	0,09	0,29	0,041	0,089
	PETP /PTFE	2	0,067	0,084	0,09	0,29	0,019	0,048
	POM C	3	0,067	0,079	0,14	0,39	0,025	0,105
	PA 66 GF30	4	0,091	0,126	0,29	0,59	0,028	0,08
	PA 6G Na	5	0,099	0,116	0,19	0,59	0,048	0,133
	PA 6G Mg	6	0,113	0,137	0,19	0,59	0,032	0,102

* - continuous change, mainly increasing tendencies

2.4. Measurements with large-scale specimens

From the aspect of tribology research, the size of the contact zone and the test specimen are of special importance. Earlier experiments have proven that the heat conduction, deformation and inhomogeneous stress distribution in natural and composite polymers can greatly influence friction and wear. Therefore, an important supplementary part of my work is planning a large-scale research system including dynamic effects, as well and evaluation of measurement results.

For the measurements, I took part in the construction of a special instrument in the Laboratory Soete at University Gent, Belgium.

The material of the steel countersurface (block) in a friction contact with the engineering plastic is a steel alloy (40CrMnNiMo8) frequently used in the European engineering practice. Its overall (inclusive) dimensions are: 90x106x420 mm. As long as in the small-scale sample testing systems, the contact zone has a size of 28.2 mm^2, in the measurement system of large-scale samples, it was 24000 mm^2. This represents an increase by a factor of 851, nearly three orders of magnitude.

I performed the measurements along with alternating motion, at several different load levels. Each measurement was performed with dual repetition, i. e. three-fold data recording. Figure 1 shows the average values of measurement series. In the environment of changes of sliding directions, acceleration sections, static and dynamic friction phenomena have occurred. In comparison with the stress levels applied at the polymer machine elements, the difference between static and dynamic friction could be accurately established due to large surface loads. Accurate knowledge of the latter can be compared with the phenomenon seen at the surface of gear teeth. In the vicinity of the pitch point the transitory rolling zone and the start/end of sliding created on the surfaces perform similar phenomenon.
The friction measured on the long, even-stroke section of the test equipment can in principle be compared with the pin-on-disc measurements performed on small-scale samples at constant speeds.

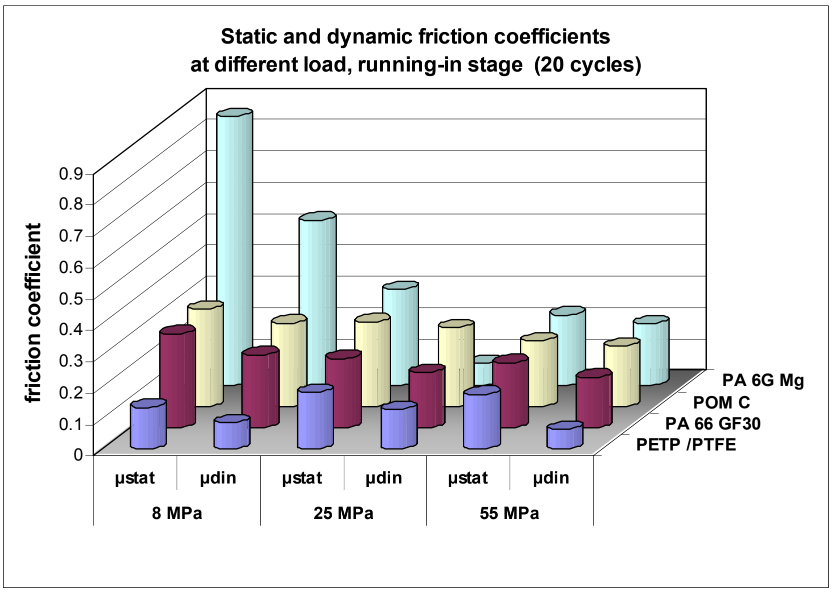

Figure1. Static and dynamic friction coefficients against normal load in the „running in" stage

2.5. Tests of gear teeth connection

During gearmesh the contacting teeth surfaces are subjected to a complex tribological effect due to rolling and sliding with changing loads. The theories of teeth contact and transmitted mechanical power are clearly written in the literature, but the friction phenomena is introduced with simplified condition, mainly taking the friction constant.
I developed a test equipment to study the real friction along the action line of mating gear teeth.

2.5.1. Developed new test equipment

For the tests concerning tooth contact, I reconstructed the base instrument used formerly for small-scale samples (Figure 2). The motor rotates the polymer gear segment via a worm-gear drive. This segment is contacted by the steel gear which has bearings on the axis knuckle of the holder head equipped with strain gauges. The constant weight load exerts its effect on the action line of gears via the rope pulley corresponding to the base circle diameter of the wheels. Regarding the plastic gear segment the angular positions of the starting and end points of the tooth contact along the action line can be accurately determined by calculations. These positions are indicated by two microswitches and the motor rotates the segment between two terminal positions by alternating rotating directions. The angular signal transmitter is located on the axis of the polymer gear segment. Its type is HEDS-5701 G00 incremental signal transmitter, with an accuracy of 0,25°.

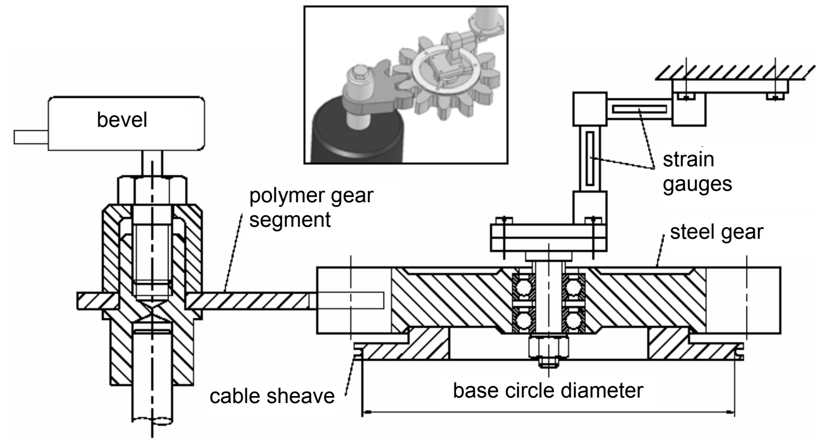

Figure 2. Draft of teeth contact tester for friction measurements

The test conditions were determined according to the polymer gear design methods.

Data of tested gears:

number of teeth: $z_1 = z_2 = 12$
modul: $m = 10$ mm
connecting angle: $\alpha = 20$ °
width of teeth: $b = 5$ mm (in case of polymer gear segment)

From the gear data, it is obvious that the wheels are undercut. For the purpose of testing, I chose such large module gears because I wanted well-defined and unambiguous friction force changes arising from sliding and rolling in the course of tooth contact. However, for the purpose of correct contact, I had to modify the OD of the gears.
The material of the mating steel gear is S 355.

The steel gear was manufactured by wire-spark erosion, the manufacturing accuracy is ±0.01 mm.
I prepared the 3-tooth polymer gear segment on a CNC milling, its thickness is 5 mm. The tested polymers are identical to the materials described at the small-scale polymer test specimens trials (Table 1).

2.5.2. Teeth friction force and coefficient

In the course of the measurements, the value of the F_y force in accordance with a conscious planning of the measurement system ended up being approximately zero, thus it can be neglected in the case of further calculation. The calculation of the friction force value in the BD single tooth contact section is described in the following section.
According to Figure 3, the following equation can be specified for the balance of forces:

$F_x = F_s \cdot \cos\alpha$

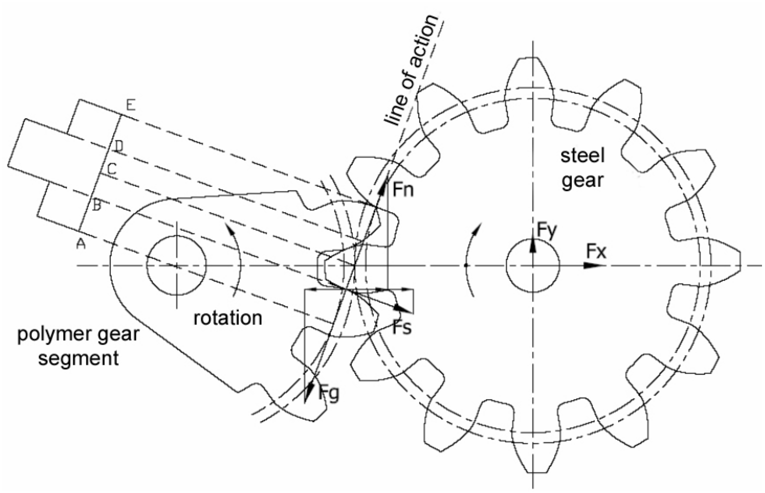

Figure 3. Single tooth contact

Friction force:

$$F_s = \frac{F_x}{\cos\alpha} \quad [N]$$

where: F_x - measured shaft force [N]
α - connecting angle [°]

In the tooth contact testing system, I defined a static and dynamic friction coefficient between the contacting tooth according to the motion characteristics, which I determined as a quotient of the friction force and the normal force. Directly before and after the pitch point where the sliding speed is near zero as well as in the pitch point where the teeth roll on one another, the friction coefficient originating from sliding in a classical sense cannot be defined due to the elastic deformation of the polymer tooth.

The calculated friction coefficient:

$$\mu = \frac{F_s}{F_n}$$

$$\mu = \frac{F_x}{F_n \cdot \cos\alpha}$$

Figure 4 depicts the change of the friction coefficient along the action line determined by calculations on the basis of measurements. In the pitch point, contacting tooth roll on one another, thus only rolling friction arises in this point. Due to deformation and elasticity of polymers, in the direct vicinity of the pitch point where sliding is near zero, contacting surfaces may experience a mutual adhesion. Due to this phenomenon, displacement may be determined by elastic deformation within the material. Therefore, I did not define the sliding friction coefficient calculated by me in the direct vicinity of the pitch point, I consciously interrupted the curve. The interruption location is a 45°contact point of the curves. Thereby, I separated the measurement results to two plus one transitory sections (according to Figure 4, Sections I, III and the transitory Section II). In the section prior to the pitch point, the sliding value continuously approximates zero whereas after the pitch point, it continuously increases from zero. This change has an effect on the value of the friction coefficient, as well.

The notation of the local maximum friction coefficient measured in a single tooth-pair contact section prior to changing of directions (concerning the friction coefficient related to rolling through the pitch point) is $\mu_{fe\text{-}max}$. Even after frictional direction change, a local $\mu_{fu\text{-}max}$ is measurable in terms of an absolute value, which has a negative sign due to directional change at the pitch point according to the scaling on Figure 4.

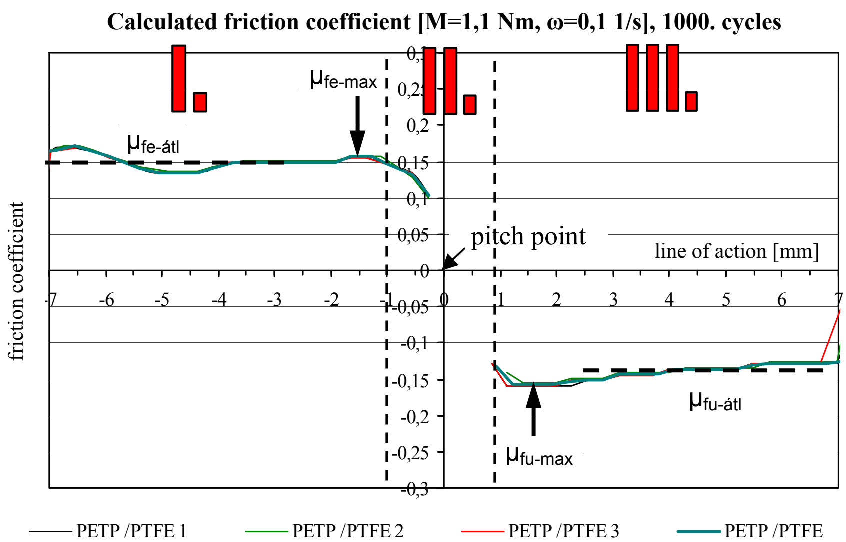

Figure 4. Friction coefficient of teeth aloong the action line

Prior to and after rolling through the pitch point, I defined the average friction coefficients at the dynamic sliding friction section, the notation of which is $\mu_{fe\text{-}átl}$, $\mu_{fu\text{-}átl}$.

In summary:

$\mu_{fe\text{-}max}$: local maximum of friction coefficient before reaching pitch point
$\mu_{fe\text{-}avr}$: average value of friction coefficient before reaching pitch point
$\mu_{fu\text{-}max}$: local maximum of friction coefficient after leaving pitch point
$\mu_{fu\text{-}avr}$: average value of friction coefficient after leaving pitch point

2.5.3. Friction results

- 1,1 Nm transmitted torque, 0,1 1/s angular velocity

Figure 5 depicts in the first tested cycle the values of the friction coefficient arising along the action line between the tested engineering polymer gear tooth and the steel gear tooth, whereas Figure 6 depicts the friction coefficient values measured at the 500. mating cycles. The load torque and the angular velocity of the rotation were identical in all cases.

The theoretical straight lines of the literature's tooth friction refer in fact to more complex surface processes which can be seen when the results of Figure 5 are inspected. In the case of tooth pairs given according to the figure, along with a constant load torque, the friction coefficient along with the action line is not constant. This phenomenon is all the more apparent in the initial stage of friction (running-in) where significant differences arise between individual material pairs.

In the event that in the vicinity of the pitch point, the local maximum of friction is clearly elevated in comparison with the friction values of the sliding sections, the "stick-slip" characteristics of the process can be recognized, as well. If this local maximum – the friction related to the smallest sliding speeds – is only slightly or not at all different from the friction values of the sliding phases, the "stick-slip" tendency is also small, thus the noise level arising from the run of the gear pair is also lower. This measurement result is in accordance with subjective observations.

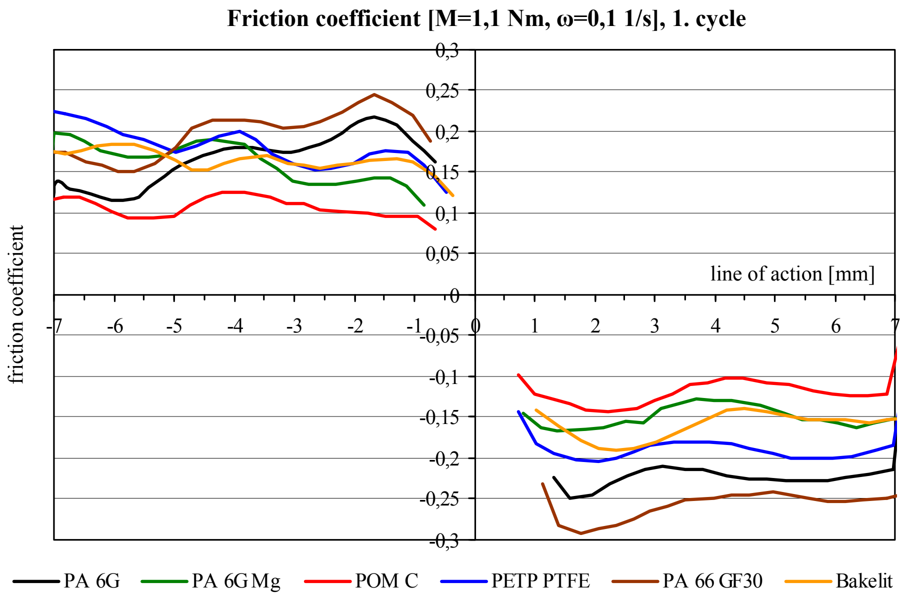

Figure 5. Teeth friction coefficient along the action line, in case of singular contact, measured in the first cycle

Figure 6. shows the measured result during the 500. cycles.

- The PA 6G "transitory phase" is the greatest around the pitch point. This cannot be clearly ascribed to adhesion phenomena, because PA 6G does not have the greatest adhesion tendency among the tested materials, but not even deformations alone can result in this phenomenon, since PA 6G has an average elasticity module. However, the most likely scenario is an overall effect, where adhesion, the formation of a transfer film, material elasticity and surface geometry together result in a relatively noisy run prone to stick-slip effects.
- The friction of the textile Bakelite starts to become unstable.
- The friction order before and after the pitch point are not identical or unambiguous anymore, the individual curves cross over one another.
- After the pitch point, PA 6G and PA 66 GF30 exhibit a definitely larger degree of friction in comparison with the other polymers (except for textile Bakelite)

- The difference between POM C and PETP/PTFE is not significant anymore. PETP/PTFE increasingly approximates the favorable friction characteristics of POM C and the addition of PTFE increasingly exerts its positive effects.

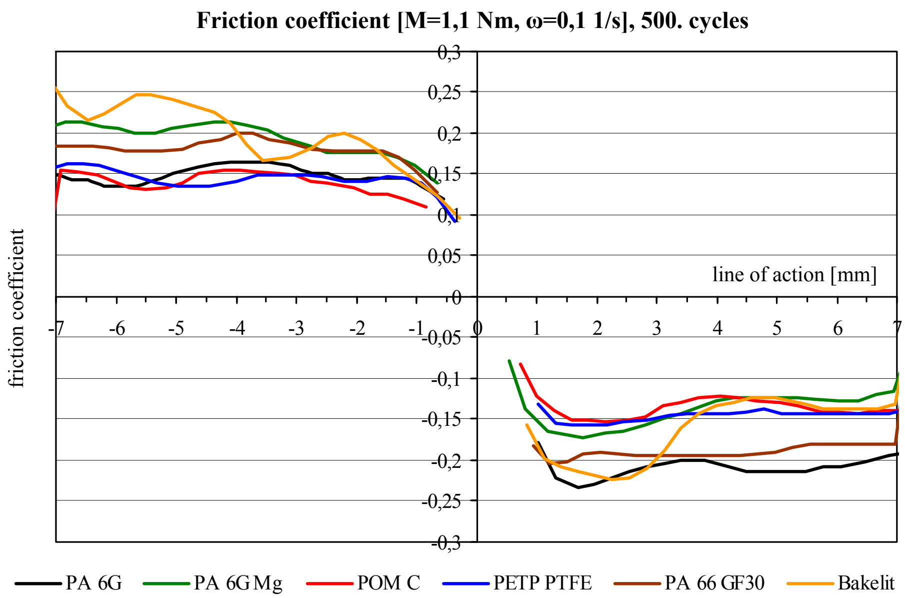

Figure 6. Teeth friction coefficient along the action line, in case of singular contact, measured in the 500. cycles

Table 4. Teeth friction result to steel mating gear (steady–state running, 1.1 Nm torque, ω=0.1 1/s)

Before reaching pitch point				After leaving pitch point			
Rank	Gear material	≈ Δμ (%)	local μ max.	Rank	Gear material	≈ Δμ (%)	local μ max.
1.	POM C	48	-	1.	PETP/PTFE	38	-
2.	PETP/PTFE	53	+	2.	POM C	34	-
3.	PA 6G	35	±	3.	PA 6G Mg	72	±
4.	PA 66 GF 30	44	±	4.	PA 66 GF 30	46	+
5.	PA 6G Mg	66	+	5.	PA 6G	30	+
6.	Bakelite	760	+	6.	Bakelite	400	+

\+ strongly differing
± recognizable
\- small or negligible difference

On the basis of Table 4, it can be clearly established that the friction order has fundamentally changed in comparison with the starting phase of running-in and separable trends can be formulated for friction processes before and after the pitch point, respectively.

- 5,5 Nm transmitted torque, 0,1 1/s angular velocity

When increasing the load moment five-fold in comparison with the previous testing system, we can make various comparisons. On one hand, comparison is possible with the friction results and trends of the lower load level, on the other hand, the behavior of individual polymers can be mutually compared.

Figure 7. depicts the friction results of the first running-in cycle in the case of a load torque of 5.5Nm.

In comparison with the results of the lower load level, the curves exhibit a different arrangement.

- PA 6G Mg responded to the increased surface pressure with a greater degree of surface deformation and adhesion, respectively, with an especially high friction value. The rolling-adhesion zone around the pitch point is especially large in comparison with other plastics.
- After the pitch point, the start of sliding is clearly moved to the pitch point, which can be explained by a greater degree of deformation arising from a larger load.
- The positions of local maxima after the pitch point exhibit a spread, as well. The greater adhesion tendency of polyamides is clearly present in comparison with POM C and PETP/PTFE.
- The textile Bakelite/steel gearwheel pair resulted in a surprisingly low friction values.
- The friction of POM C has deteriorated in comparison with results obtained at smaller load levels whereas in the case of PETP/PTFE, an improvement can be detected.
- The interval of friction coefficients is fundamentally identical at the two load levels, but at higher load levels, clear rank orders cannot be established anymore (as it is possible at lower load levels) because the friction curves of individual materials are not identical in their slopes or characteristics and numerous curves intersect one another.

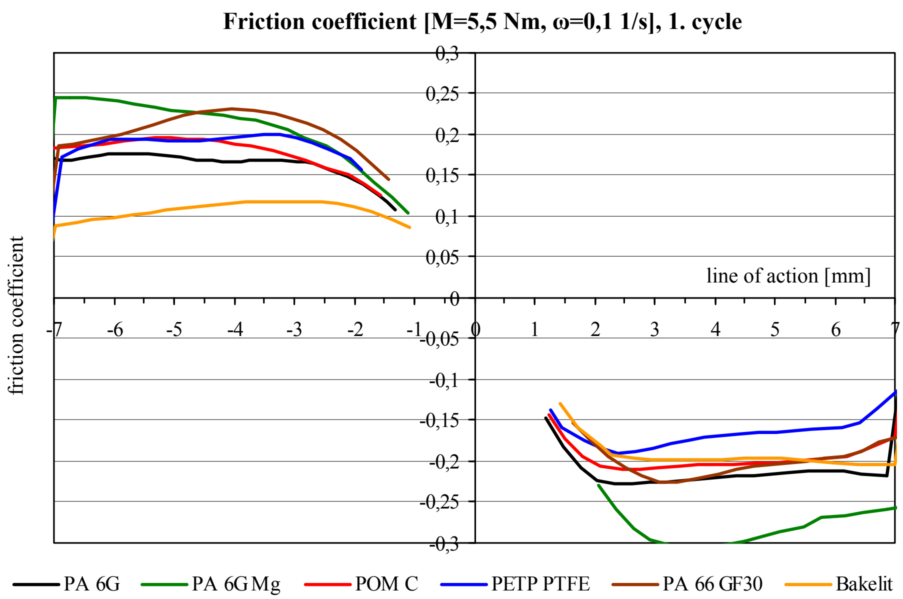

Figure 7. Teeth friction coefficient along the action line, in case of singular contact, measured in the first cycle, at elevated load level

Upon reaching the 500. cycles (Figure 8), a clear trend of friction can be observed, no fundamental difference occurs before and after the pitch point, respectively, only the absolute values of friction are different.

- The PETP /PTFE, PA 66GF30, POMC, PA 6G Mg, PA 6G and textile Bakelite order is clear.
- Textile Bakelite violates all known characteristics and trends, especially its friction after the pitch point exhibits a highly intensive adhesion tendency.
- The PETP /PTFE composite is still the best, the absolute value of the friction coefficient has further decreased in comparison with the 100. cycle, the PTFE additive exerts the relevant effect in the course of sliding.
- Upon comparing polyamides, it is conspicuous that the friction of the glass fiber filled PA 66 is smaller than the natural cast polyamide 6 versions.
- No significant difference occurs in the case of POM C and PA 6G Mg, the local maximum after the pitch point is reduced in the case of PA 6G Mg, in comparison with the 100. cycle.
- On the other hand, the Na-catalyzed PA 6G exhibits a much more unfavorable friction characteristic than Mg-catalyzed PA 6G Mg. This can be related to an earlier phenomenon, namely that in the case of PA 6G Mg, the transfer film occurs earlier and it is thicker on the metal surface, which plays an important role in retaining a dynamic friction balance.

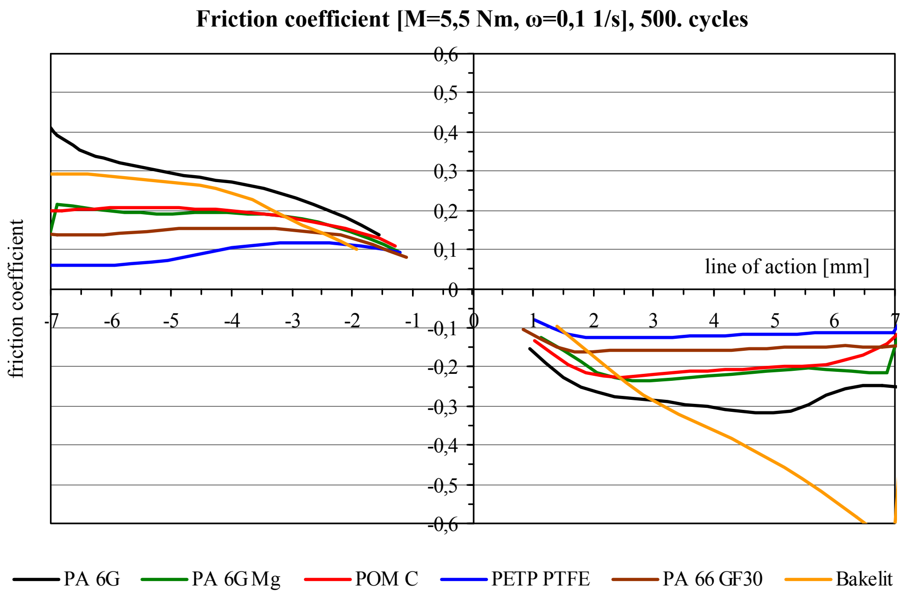

Figure 8. Teeth friction coefficient along the action line, in case of singular contact, measured in the 500. cycles, at elevated load level

Table 5. Polymer teeth friction result to steel mating gear (steady–state running, 5.5 Nm torque, ω=0.1 1/s)

Before reaching pitch point				After leaving pitch point			
Rank	Gear material	Rank	Gear material	Rank	Gear material	Rank	Gear material
1.	PETP/PTFE	35	±	1.	PETP/PTFE	2	-
2.	PA 66 GF 30	25	-	2.	PA 66 GF 30	44	-
3.	POM C	90	-	3.	POM C	85	±
4.	PA 6G Mg	380	-	4.	PA 6G Mg	360	+
5.	PA 6G	270	-	5.	PA 6G	330	+
6.	bakelite	260	-	6.	bakelite	210	+

+ strongly differing
± recognizable
- small or negligible difference

Based on table 5. we can state that the friction order comparing to the lower load level has changed, different trends can be defined before and after the pitch point.

2.6. Comparison of the different test systems

Table 6. and 7. give a brief summary about the research systems and correlations, regardless the system-dependent absolute values of friction coefficients.

Table 6. Correlation between friction ranks measured in the running-in of gearmesh

	Real gear teeth friction, running-in state
Small-scale samples, dynamic conditions	- Relation between POM C and polyamides is similar
	- Relation between Bakelite and thermoplastics is not similar
	- Among polyamides the ranking is different
	- Relation between PETP/PTFE and PA 6G, PA 66GF30 is similar
Large-scale specimen tests	- Relation between POM C and PA 6G Mg is similar
	- Relation between POM C and PETP/PTFE is not similar
	- Relation between PETP/PTFE and PA 6GMg and PA 66 GF30 is similar
	- Relation between PA 66 GF30 és POM C is not similar

Table 7. Correlation between friction ranks measured in the steady-state of gearmesh

	Real gear teeth friction, steady state
Small-scale samples, pin-on-disc tests	- Relation between POM C and PA 66 GF30 is not similar
	- Relation between Bakelite and thermoplastics is similar
	- Among polyamides the ranking is different
	- Relation between PA 66GF30 and other natural PA6 is similar
	- Relation between PA 6G Mg and PA 6G Na is not similar
	- Relation between PETP/PTFE and other tested materials is similar
Large-scale specimen tests	- Relation of PETP/PTFE to the other tested materials is similar
	- Relation of PA 66GF30 to the other tested materials is similar
	- Relation of POM C to the other tested materials is similar
	- Relation of PA 6G Mg to the other tested materials is similar

3. NEW SCIENTIFIC RESULTS

1. I have elaborated a measurement method and a measuring system for determination of the friction force occurring in the course of contact between involute gear tooth profiles. The measurement system measures the friction force components arising between the contacting teeth in the single tooth pair contact section.

2. I have established that along the action line, the measured friction force changes as a function of drive. In the course of tooth contact of polymer-steel gears, in the vicinity of the pitch point, the relationship between rolling and sliding depends on material pairing. For individual material pairs, I have determined the transitory range arising in the vicinity of the pitch point and its change as a function of running (number of test cycles).

3. The friction coefficient between polymer/steel tooth pairs is not constant in the case of constant load torque and gear’s rotation number, along the action line. I have determined the average sliding friction coefficient before the pitch point, the maximum local friction coefficient prior to the pitch point, the transitory sliding-adhesive zone characteristic of the pitch point and its vicinity, the local friction coefficient maximum after the pitch point and the average friction coefficient. The adhesive-sliding tendency of the material pair is characterized by the size of the sliding-adhesive transitory phase after the pitch point and the local friction maximum measured after the pitch point.

4. I have established that in comparison with the running-in state, a friction reduction of 5-10% occurs in the steady-state, irrespective of the load, in the case of PETP/PTFE and steel gear pairing, which can result the increase of driving efficiency. At a small load level (19.5MPa max. Hertz stress), the POM C friction has stabilized and prior to the pitch point, the friction coefficient slightly increases during use. Increasing load (43.5 MPa max. Hertz stress) has moved the friction of POM C to an unfavorable, slowly increasing direction. This statement is equally valid for friction characteristics prior to and after the pitch point.

5. Natural cast polyamide 6 types and glass fiber reinforced extruded polyamide 66 reacted differently to the increase of the load level. At a small load level, there was no significant difference between polyamides in a stabilized state. The friction coefficient of PA 66 GF30 only exceeded by 12% that of natural materials in the running-in phase. The friction of polyamides slightly increase as a function of the time period of use. At a greater load level, the friction loss of natural cast polyamide materials increased by 50% on the average whereas the friction of PA 66 GF30 stabilized at a 10% lower level in comparison with the running-in.

6. The friction coefficient of the textile Bakelite (thermoset, cresol formaldehyde resin + textile cloth) is decreased during use, irrespectively of load. In a system without lubrication, the friction characteristics are fundamentally different from thermoplastic engineering plastics. No friction balance has formed in the case of textile Bakelite.

7. I have studied the friction characteristics of material pairs by preliminary experiments, with small-scale samples under static circumstances using “pin-on-disc” and dynamic “pin-on-plate” model testing systems as well as with large-scale samples, in dynamic (“plate-on-plate”) systems. In the definition domains of testing system, I have established relative friction orders with respect to the running-in and the steady-state, respectively. I have compared the results of static and dynamic systems with the results obtained in the tooth contact testing system and I have established partial, material-dependent, limited correlations between individual testing systems.

7/a, In the definition domains of testing systems, relative teeth friction ranking can be described for running-in state based on dynamic pin-on-plate test method: in relation of POM C and PA 6G, PA 6G Mg mating with S355 steel, furthermore in relation of PETP/PTFE and PA 66 GF30 mating with S355 steel.

7/b, In the definition domains of testing systems, relative teeth friction ranking can be described for running-in state based on large-scale block-on-plate test method: in relation of POM C and PA 6G Mg mating with S355 steel, furthermore in relation of PETP/PTFE and PA 6G Mg and PA 66 GF30 mating with the used steels.

7/c, In the definition domains of testing systems, relative teeth friction ranking can be described for steady-state based on pin-on-disc test method: in relation of Bakelite and the tested thermoplastics mating with S355 steel, furthermore in relation of PA 66 GF30 and PA 6G, PA 6G Mg mating with S355 steel, furthermore in relation of PETP/PTFE and the other tested materials mating with S355 steel.

7/d, In the definition domains of testing systems, relative teeth friction ranking can be described for steady-state based large-scale block-on-plate test method: in relation of all the tested polymers (PETP/PTFE, POM C, PA 66 GF30, PA 6G, PA 6G Mg) mating with the used steels.

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