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THEORETICAL CONTRIBUTIONS ON THE SELECTION OF POSSIBLE TRIBOLOGICAL COUPLES OF MATERIALS FOR THE MANUFACTURE OF PRECESSIONAL TRANSMISSIONS

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Abstract. Selecting gear materials is a great challenge for engineers. Gear teeth are subject to difficult and severe loading conditions. Simultaneous action of alternating normal and tangential dynamic stresses occurs, contact deformations accompanied by sliding friction. Gears are subject to increased requirements in terms of strength, geometric accuracy, dimensional stability, and durability. For the manufacture of gears, especially from thermoplastic materials, a theoretical argumentation of the materials is needed. An extensive study of thermoplastic materials, around the world needs to be done and the most efficient tribological couples to be chosen in terms of heat transfer from the gear zone, operation with or without lubrication, and gear life. In this paper, a theoretical synthesis of the Steel / Plastic, Plastic / Plastic, Plastic/Steel tribological couples is made, which were used in conformist and non-conformist experiments. Therefore, selected tribological couples are supposed to be used in the Precessional Transmissions applications.

Keywords: *gear materials, sliding friction, manufacture of gears, thermoplastic materials, heat transfer, tribological couples, gear life, theoretical synthesis.*

Rezumat. Selectarea materialelor pentru angrenaje este o mare provocare pentru ingineri. Dinții angrenajului sunt supuși unor condiții de încărcare dificile și severe. Are loc acțiunea simultană a tensiunilor dinamice normale și tangențiale alternative, deformații de contact însoțite de frecare de alunecare. Angrenajele sunt supuse unor cerințe sporite în ceea ce privește rezistența, precizia geometrică, stabilitatea dimensională și durabilitatea. Pentru fabricarea angrenajelor, în special din materiale termoplastice, este necesară o argumentare teoretică a materialelor. Trebuie făcut un studiu amplu al materialelor termoplastice în întreaga lume și să fie alese cele mai eficiente cupluri tribologice în ceea ce privește transferul de căldură din zona angrenajului, funcționarea cu sau fără lubrifiere și durata de viață a angrenajului. În această lucrare se realizează o sinteză teoretică a cuplurilor tribologice Oțel / Plastic, Plastic / Plastic, Plastic / Oțel, care au fost utilizate în experimente conformiste și nonconformiste. Prin urmare, cuplurile tribologice selectate ar trebui să fie utilizate în aplicațiile de transmisii precesionale.

Cuvinte cheie: *materiale de angrenaj, frecare de alunecare, fabricare angrenaje, materiale termoplastice, transfer de căldură, cupluri tribologice, sinteză teoretică.*

Introduction

The choice of materials is an important and difficult stage in the design of solar wheels and satellites in the gears with Precessional Transmissions (PT), [1, 2]. Although in this field and not only the cost of the material is generally low compared to the cost of labor either by mechanical processing or injection into the die. The choice of materials must take into account some criteria related to the use and manufacture of the elements in the gear. From a functional point of view, for good operational behavior, resistant parts with low specific weight are required. As a result, the ratios between the allowable resistance σ_a or τ_a and the specific gravity ϒ must be as high as possible, [3]

$$\frac{\sigma_a}{\gamma}\ and\ \frac{\tau_a}{\gamma} \tag{1}$$

Reports of the type

$$k_\sigma = \frac{\sigma_a}{\gamma} \tag{2}$$

called material strength characteristics *(k_σ)* and are influenced by stress.
Weight ratio G_1 and G_2 will be:

$$\frac{G_1}{G_2} = \frac{\gamma_1 A_1}{\gamma_2 A_2} = \frac{\gamma_1}{\gamma_2} : \frac{\sigma_{r_2}}{\sigma_{r_1}} \tag{3}$$

Where: A_1 and A_2 are the areas of the sections; σ_{r_1} and σ_{r_2} breaking limits, [3].

For bending stress (the situation is similar for torsional stresses) on parts with the same sections can write, [3]:

$$\frac{W_1}{W_2} = \frac{\sigma_{i_2}}{\sigma_{i_1}} = \left(\frac{A_1}{A_2}\right)^{3/2} \tag{4}$$

Where: W_1 and W_2 bending strength modulus of the sections A_1 and A_2, σ_{i_1} σ_{i_2} bending stresses. It follows:

$$\frac{G_1}{G_2} = \frac{\gamma_1}{\gamma_2} . \frac{A_1}{A_2} = \frac{\gamma_1}{\gamma_2}\left(\frac{\sigma_{i_2}}{\sigma_{i_1}}\right)^{2/3} = \frac{\sigma_{i_2}{}^{2/3}}{\gamma_2} : \frac{\sigma_{i_1}{}^{2/3}}{\gamma_1} \tag{5}$$

It follows that the strength of the elements influences to a greater extent the specific weight of the materials at the stress of stretching-compression than at the stress of bending. Also to get rigid parts with low specific weight need, [3]

$$\frac{E}{\gamma}\ si\ \frac{G}{\gamma} \tag{6}$$

the ratio between the modulus of elasticity of materials E or G and the specific gravity γ should be as high as possible, [3].

Reports of the type

$$k_r = \frac{E}{\gamma} \tag{7}$$

they are called stiffness characteristics and are also related to the masses of the elements and the stress [3]. In Figure 1 are presented the strength of generic materials.

From a technological point of view, the choice of materials must take into account the possibilities of their processing, as appropriate, by casting, pressing, rolling, stamping, cutting, and the ability of the material to form, by chemical and galvanic coatings resistant layers corrosion to other environmental agents [3].

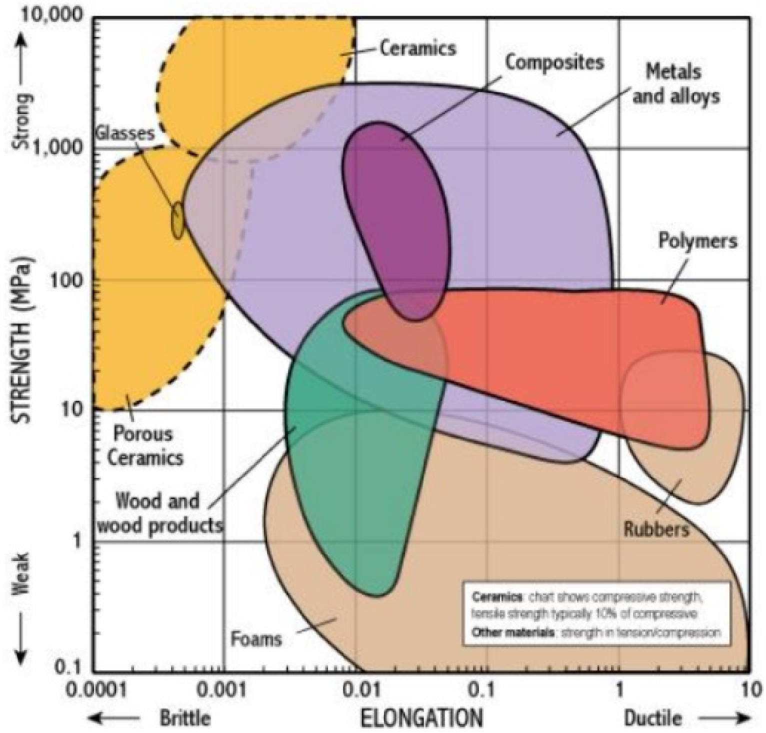


Figure 1. Strength of materials, [4].

In all the design stages, when choosing the material, the economic criterion must also be taken into account, following their cost and the fact whether or not it is deficient. Depending on the character of the production (mass, in large or small series), the ratio between the cost of the material and that of processing varies, [3]. Thus, in mass production due to the automation and mechanization of production processes, the cost of processing becomes lower than that of the material. However, it is not advisable to try to reduce production costs by using cheaper, lower-quality materials, because the results of mechanization and automation of production are conditioned by the use of homogeneous materials, both dimensionally and in terms of technological properties. On the other hand, in small series production, the share of the material in the cost of the part is small in relation to the cost of processing, the latter encompassing the work of the highest qualification. Under these conditions, it is found that it is cost-effective to use more expensive but higher quality materials when necessary (for ex. PEEK or PBI). All materials with industrial value are used in the manufacture of gears. Thus, ferrous materials, non-ferrous metals, and their alloys, thermoplastic materials, are used. Higher quality carbon steels are used in the manufacture of gears that require high strength even without the use of heat or thermochemical treatments. Such alloys are *OL 70, OLC 55,* [3], if precise processing and resistance of the teeth are pursued without a heat treatment, which could cause their deformation. However, it should be remembered that these steels are not easy to process, the tools are worn faster than those used for low carbon steel, [3].

Alloy steels and higher alloy steels for machine building are often used for the manufacture of gears, especially those with chromium as an alloying element *(40 Cr10),* [2]. Consequently, alloy steels are much less deformed by heat treatment than carbon steels, this conclusion being of great importance for small and precise parts whose further hardening processing is difficult and sometimes impossible due to their small size.

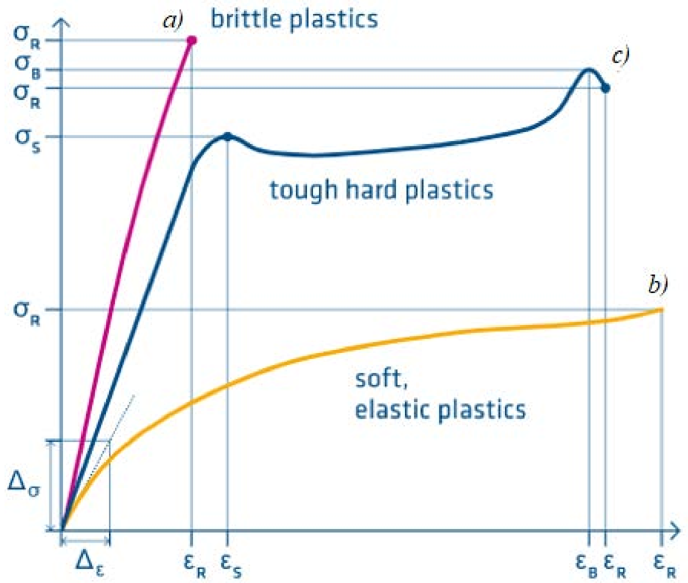
It should be noted that steel is in itself an ideal solid matter or in other words a Euclidean rigid with linear Hooke's behavior. Compared to thermoplastics which are real fluid bodies with Maxwellian behavior, [5]. Thermoplastics are viscoelastic bodies that, under the action of force, the viscoelastic body "flows" but also deforms elastically. Some of the *(Wr)* energy accumulates in the form of reversible deformation. The other part of the *(Wc)* energy is consumed to achieve the irreversible deformation in the flow process, it dissipates in the form of heat. The total energy(*Wa*), transferred to the viscoelastic body is consumed to achieve its deformation and flow, [5].

$$W_a = W_r + W_c \quad (8)$$

A fluid can be considered perfectly viscous if the effects of its elasticity properties are negligible, *Wr* tends to 0. A real solid can be considered perfectly elastic if the effects of its viscosity properties are negligible, *Wc* tends to 0. The deviation from the perfectly elastic behavior of elastoviscous solids is due to the viscous effect *Wc* and the deviation from the perfectly viscous behavior of viscoelastic fluids is the result of the elastic effect *Wr*, [5]. A similar explanation of the rheological behavior of thermoplastic only in terms of the ratio between the relaxation time and the time of the material called the Deborah number is made by Poole R.J. [6].

When designing a thermoplastic gear wheel it is necessary to know the rheological deformations, thus a solid or liquid body, henceforth thermoplastics, unlike steels, depending on the mechanical stresses can have the following states of aggregation: elastic solid, viscoelastic fluid, viscous fluid, [5].

The application of an external force on a polymer triggers a structural reaction, which is located at the molecular or supramolecular level depending on the intensity of the stress and the presence of defects that focus the elastic energy. The way in which the polymer responds to mechanical stress is determined by its physical state and materializes in the deformation processes. The deformation of complex structures, of the nature of polymers, is composed of a succession of specific phenomena, from the elastic behavior to the viscous one, [5].



σ_B Ultra-high tension ε_B Elongation under ultra-high tension

σ_R Tensile strength at break ε_R Elongation at break

Figure 2. The behavior of thermoplastic polymers, during the quasi-static uniaxial deformation: a) Brittle (eg. PS at room temperature); b) Soft (PTFE at 100°C); c) Tough hard plastic (PA.6 at room temperature), [7].

In Figure 2 shows examples of the behavior of thermoplastic polymers, during the quasi-static uniaxial deformation, in the temperature region corresponding to the vitreous state. The stress-strain curve (a) is characteristic for brittle polymer (eg. polystyrene at a temperature that is characterized by a very limited elongation and a rapid monotonous increase in strain stress). Curve (b) represents the behavior of a soft elastic polymer (eg. PTFE at 100 0C), it is characteristic of polymers with low (soft) hardness, those at a temperature close to glass transition (Tg), or for plasticized ones, which have not yet become highly elastic. Curve (c) describes the behavior of a hard rigid plastic polymer. The initial monotonous increase of stress is generally slower than of a brittle polymer, the secant modulus is smaller, [5].

1. Polymers as substitute materials in the steel gears

Polymers are used as substitute materials in steel gears due to their technical and economic advantages. Compared to the metal ones [9], the advantages of polymer gears are: low specific gravity [10], no maintenance is required [11], high wear resistance in a dry condition (auto lubrication) [12], low noise, [13]; vibration damping, [14]; corrosion resistance; resistant to chemical solvents [15]; moment of inertia and low mass [16]; low cost production figure 3, [17], possibility of recycling. And the disadvantages are presented in the form of: requires increased attention to operating temperature [18], lower mechanical and thermal properties compared to ferrous and non-ferrous materials, [19], low manufacturing tolerances, [20].

Metal gear: 22.10 cm^3
When SG is 7.8, weight is 172.4 g

Plastic gear: 9.26 cm^3
When SG is 1.3, weight is 12.04 g

Figure 3. Advantages of manufacturing die-cast gears compared to other manufacturing technologies, [17].

Figure 4 shows an example of calculating the manufacturing costs of a steel gear wheel and a plastic one. Sintered metal gear cost $2.33 = powder metal $1.10 + sintering $1.00 + secondary $0.23, or machined metal gear $2.80 = metal blank $0.60 + machining $2.20 vs. plastic gear $0.73 = resin $0.48 + injection molding $0.25, [17].

Therefore it can be said that thermoplastics are ideal to replace metal gears. It offers flexibility in design and increased performance throughout the exploitation.

Fillers, fibers, and additives, Figure 4 - are substances added in low concentrations in polymers to improve (from 30% to 40%) physical, chemical, electrical properties, to facilitate production or to change these properties, [21, 22, 23]. Due to the great diversity of polymers, fields of use, it is difficult to classify the polymers used in the manufacture of gears. A simplified classification of polymers is shown in Figure 5.

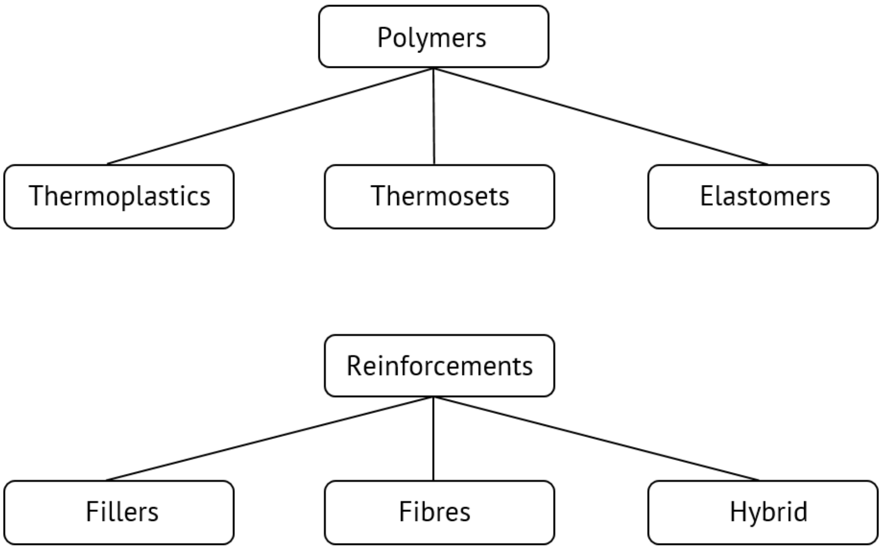


Figure 4. Simplified classification of polymers and their reinforcements, [24, 34].

Based on experimental research conducted by scientists around the world, the most commonly used basic resins with a pure crystalline structure used in the manufacture of gears are highlighted: unsaturated polyester resins (PA6 și PA66), polyacetals (POM), polyphenylene sulfide (PPS), polyether ether ketone (PEEK) and polybenzimidazole (PBI), materials which are used in the pure and composite states (reinforced with fibers, fillers, lubricants, etc.), [21-84].

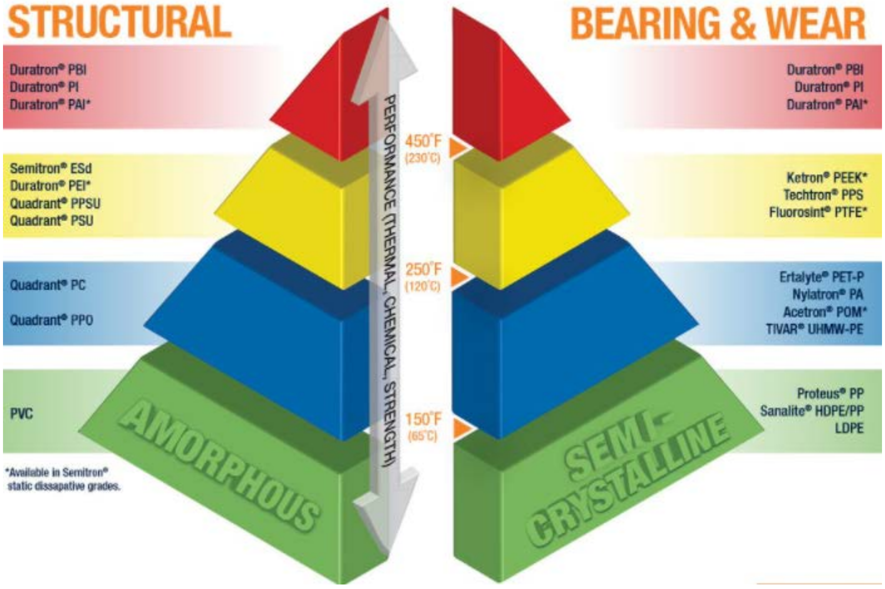


Figure 5. Mitsubishi chemical advanced materials, [24]

It is not possible to make a universal gear for all possible types of applications, the purposes of the gear must be identified:

- Moment, impact, rigidity;

-Thermal (temperature field and maximum use temperature);

-Environment of use (water, cosmic space, humidity and ambient air temperature, etc.);

-Identification of the chemical environment - defining chemical requirements, temperature, contact time;

-Identification of specific requests – the action of ultraviolet waves, opaque or transparent, resistance to fatigue and deformation under the continuous application of forces;

-Defining of the manufacturing processes – injection molding, mechanical processing, etc.;
-Assembly, plating, gluing, welding, etc.; [25].
- Availability and accessibility of thermoplastic material.

2. Theoretical argumentation of materials and tribological couples for classical gears: Plastic/Plastic, Steel/Plastic, Plastic/Steel

In order to replace steel gears with plastic gears, the operating environment, stiffness, weight, material properties, and cost must be considered [25].

Standards for the design of plastic gears are known: AGMA, British Standard, and German Standard VDI 2736, [26]. Compared to steel, defects in polymeric gears are different due to the properties of thermoplastics, for example, the defect often encountered in polymeric gears is tooth melting (thermal damage).

2.1 Theoretical argumentation of Plastic/Plastic tribological couples

K. Mao et al. [27] found that the wear of the POM / POM gears is different from the NYLON gears (PA6 / PA6). The POM gear is damaged in a high torque field for thermoplastics (10-16.1 N*m). But for the NYLON (PA6 / PA6) gear, the damage occurred at the maximum 10 N*m moment, (Figure 6).

a) b)

Figure 6. Wear of gear wheels made from: a) Nylon (PA6), b) Acetal (POM), module 3 mm, 30 teeth, [27].

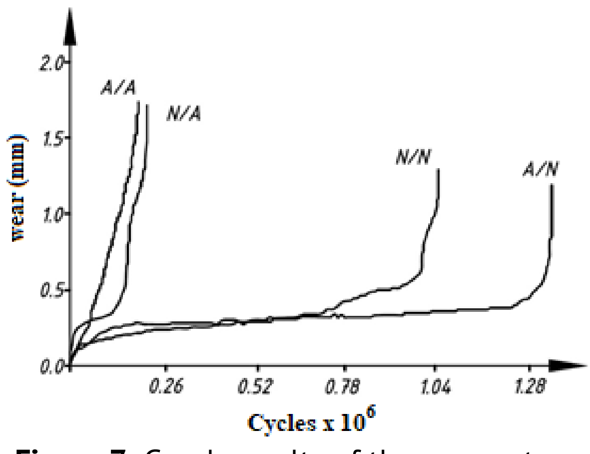


Figure 7. Graph results of the wear rate:
PA6 / POM (N/A), POM / PA6 (A/N), POM/POM (A/A), PA6/PA6 (N/N), [28].

Marcel Suciu [29] and K. Mao [30] found that the primary influence on the wear of the teeth of the gears made from POM has the manufacturing process, mold die or by cutting. In [29] mentioned that the tripling of the pressure holding time, respectively from 7 to 20 sec. and at the same time doubling the piston pressure, from 200 to about 400 kg/cm^2, reduces from 7% to 3% the content of low molecular weight fractions and creates the possibility of raising the accuracy of the parts with a class. Mao et al. [27] noted that the gear wear influenced by temperature and service life. The appearance of the temperature is due to the friction, that occurs while sliding/rolling effect of the gear teeth. The results of the tests were introduced in two-dimensional graphs, Figure 8 and Figure 9, [27].

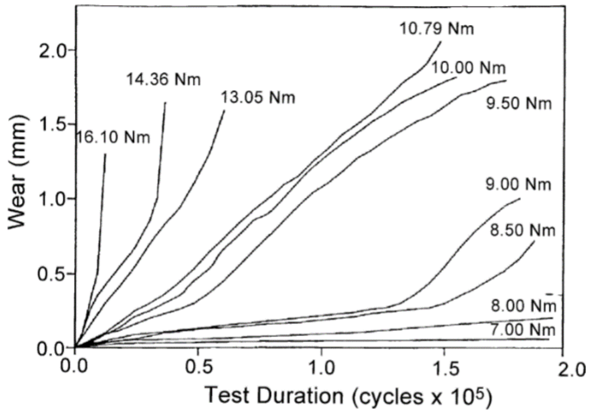


Figure 8. POM / POM gear wear and service 15PTFE life at various moments.

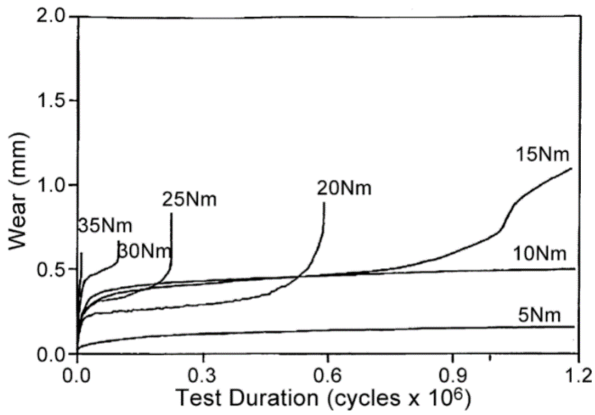


Figure 9. PA66 30GF 15PTFE/ PA66 30GF gear wear and service life at various moments.

From Figure 8 it is observed that for the proper functioning of the POM gear pairs the maximum moment of 8 N*m is recommended. For the *PA66 30GF 15PTFE/ PA66 30GF 15PTFE*pairs, the wear is higher but can be transmitted moments up to 10 Nm, (Figure 9).

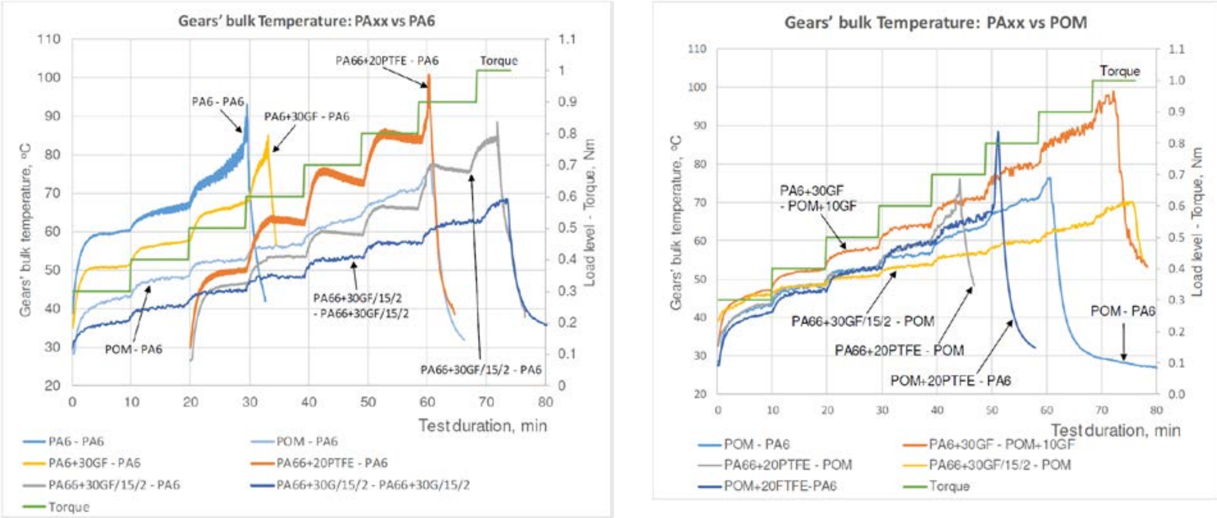
Other research carried out on plastic/plastic gears was performed by Jože TAVCAR and others [31], on PA6, PA66, POM, and PPS materials, reinforced and unreinforced ones, (Table 1).

Table 1

Tested polymer materials, [31]

Polymer abbreviation	Polymer description
PA6	PA6 Polyamid; Ultramid® B3S, BASF
PA6+30GF	PA6 + 30% Glass Fiber; Zytel 73G30L NC010, DuPont
PA66+20PTFE	PA66 + 20% PTFE + SI; LNP C, RP004 (RL-4540), Sabic
PA66+30GF/15/2	PA66 + 30% Glass Fiber + 15% PTFE + 2% SI; LUVOCOM, Lehmann&Voss
POM	POM Polyacetal; Delrin® 500P, DuPont
POM+10GF	POM + 10% Glass Fiber; Delrin® 510GR NC000, DuPont
POM+20PTFE	POM + 20% PTFE; Delrin® 520MP NC010, DuPont
PPS+30CF/15	PPS + 30% Carbon Fiber + 15% PTFE; LNP LUBRICOMP C, OCL36A, Sabic

They used an original testing procedure consisting of the following steps: preliminary design of gears, (choice of material and preliminary calculation of the gear), testing (increasing the moment step by step), life cycle testing, detailed design of gear (accurate calculation of the gear based on the test results), gear testing in the final application and product validation. The life cycle results of the gear pairs of different materials are shown in Figures 10 and 11, [31]. PA66 30GF 15PTFE2Si / POM 20PTFE the longest-lived pair of gears made from, figure 11, [31]. In Table 2 are presented the friction coefficients calculated depending on the temperature in the gear, [31].



a) b)

Figure 10. a) The PA gears (with different fillers) bulk temperature during the step test. b) The PA6 and PA66 / POM gear pairs temperatures.

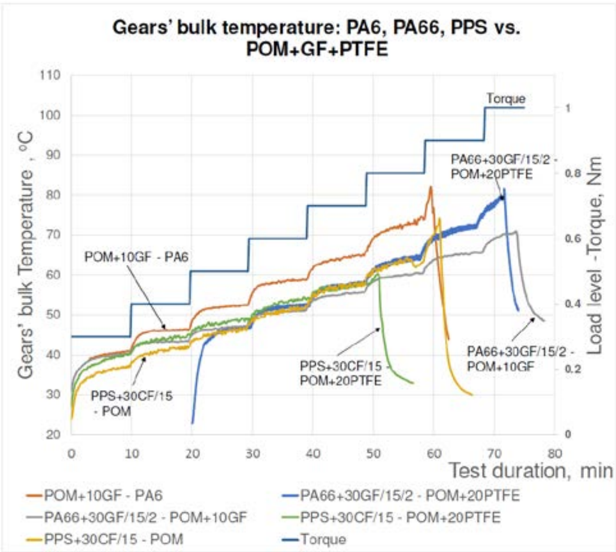


Figure 11. The PA and PPS in pair with POM gears (with different fillers) temperature profiles during the step test. Note that one test was carried out from the 0.5 Nm of torque onwards.

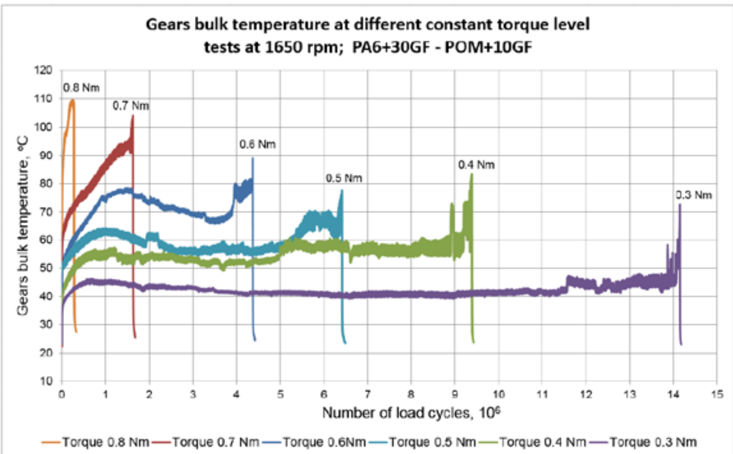


Figure 12. Gears bulk temperature profiles during several life span tests of PA6+30GF – POM+10GF material pair.

Table 2

Polymer material pairs and calculated indicator of CoF on the basis of gear bulk temperature measurements

Material pair	μ - Indicator of CoF
PA6 – PA6	0.53
PA6+30GF – PA6	0.45
PA6+30GF – POM + 10GF	0.34
POM + 20PTFE – PA6	0.29
POM – PA6	0.29
PA66 + 20PTFE – POM	0.29
POM +10GF – PA6	0.29
PA66 + 20PTFE – PA6	0.27
PA66 + 30GF/15/2 – POM	0.27
PPS + 30CF/15 – POM + 20PTFE	0.25
PA66 + 30GF/15/2 – PA6	0.23
PA66 + 30GF/15/2 – POM + 20PTFE	0.22
PPS + 30CF/15 – POM	0.22
PA66 + 30GF/15/2 – POM +10GF	0.22
PA66+30GF/15/2 – PA66 + 30GF/15/2	0.21

Figure 12 are shown the primary influence of temperature on the life cycle of the polymer gear. All pairs were tested until the complete damage. The defects in the gears were analyzed optically (Figures 13 – 16) [31].

Figure 13. Sudden tooth fracture failure of POM gear is caused by fatigue and lunker created in the injection molding.

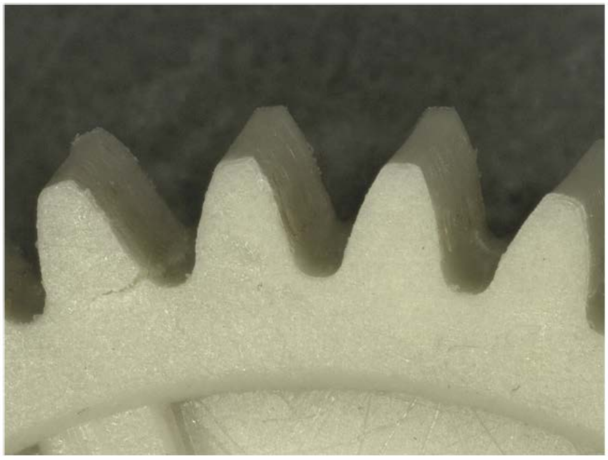


Figure 14. Crack in the tooth root of reinforced PA6+30GF gear is caused by fatigue, 15 million load cycles at 1650 rpm and 0.3 Nm load level.

The applications of PTFE lubricant in the pure PA polyamide matrix reflect a low coefficient of friction. As a result, the gear operates at lower temperatures. The use of the combination PTFE-POM does not significantly improve the tribological performance of the gear. The coefficient of friction is determined on the basis of temperature measurements. The exact determination of the temperature in the gear optimizes the design of the gears.

Fiberglass-reinforced polymers significantly increase durability at high moments (Figure 10a, b and Figure 11).

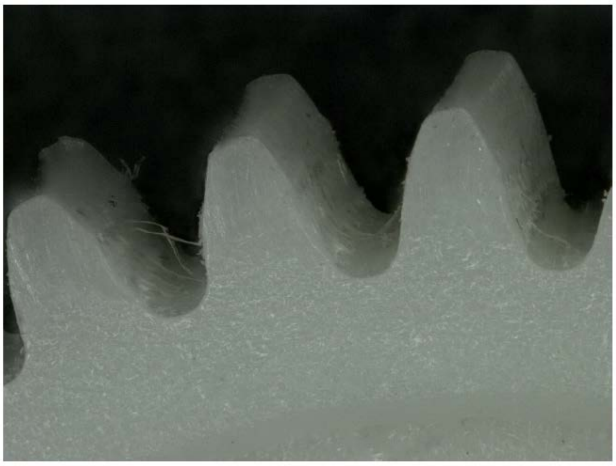


Figure 15. Wear damage on reinforced POM+ 10GF gear in pair with PA6+30GF after step test.

Figure 16. Fatigue failure mode of reinforced PPS+ 30CF/15 in pair with POM after 0.77 million load cycles at 1650 rpm and 0.5 Nm load level.

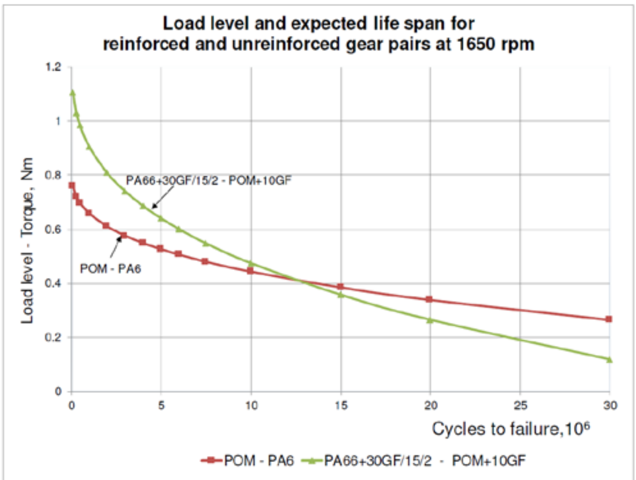


Figure 17. The PA6+30GF/POM and PA6+30GF/ POM+10GF gear pairs load level in relation to the cycles to failure.

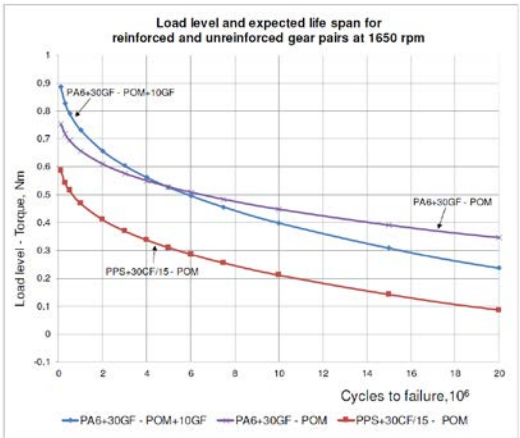


Figure 18. The PA6+30GF/POM and PA6+30GF/POM+10GF gear pairs load level in relation to the cycles to failure.

The transmission torque decreases more slowly in the unreinforced pairs than the reinforced ones. At the higher number of cycles (10^7) it is necessary to check whether it is not better to apply unreinforced materials, [31].

Hoskins et al. analyzed the tribological performance of two PEEK 450G disks (position 7 in Figure 19), [32].

They analyzed temperature-dependent time of pure PEEK disks, (Figure 20). Concluded that the wear of PEEK pairs is much lower than for other polymers. At high loads, the surfaces of the discs are deformed and melted, observable with the naked eye, [32].

Nonconformist tribological research was also done by D.H. Gordon and S.N. Kukureka [33] with discs from PA46 (Figure 21) unreinforced and reinforced with aramid fibers 6,%, 12%, 15%.

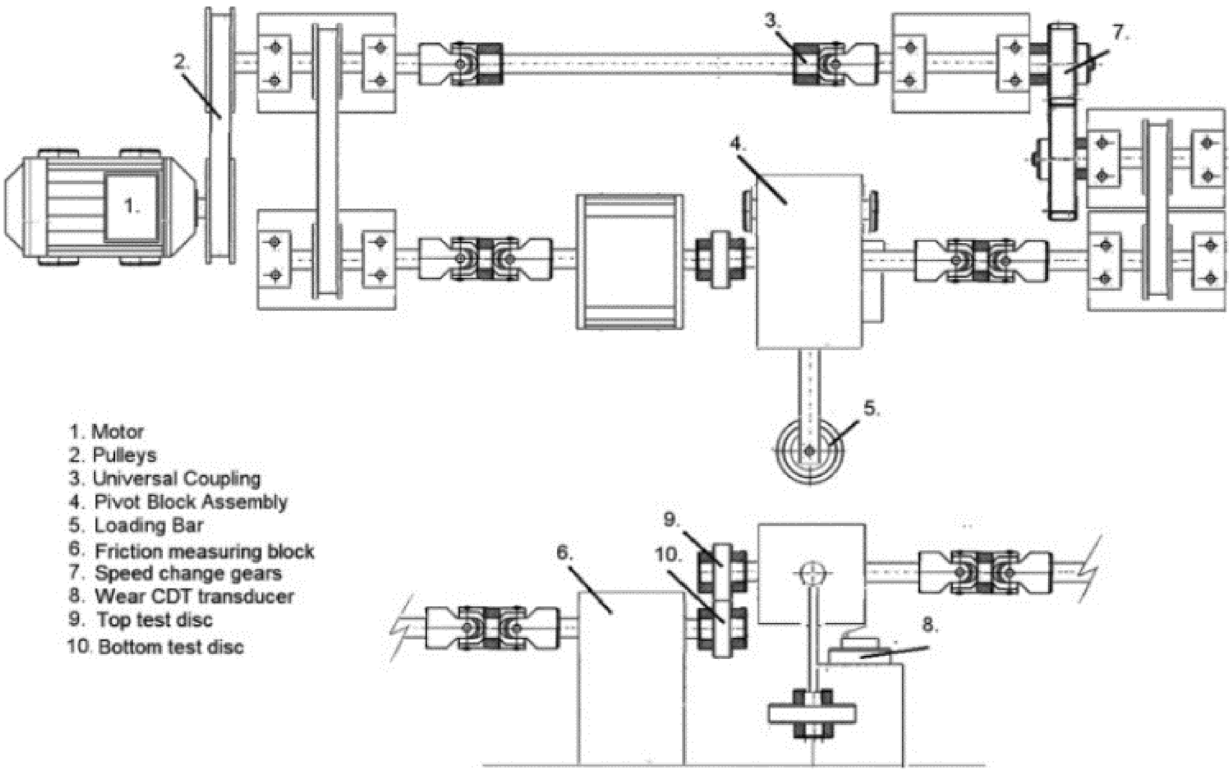


Figure 19. Schematic presentation of the experiment on establishing the tribological performance of two PEEK 450G disks.

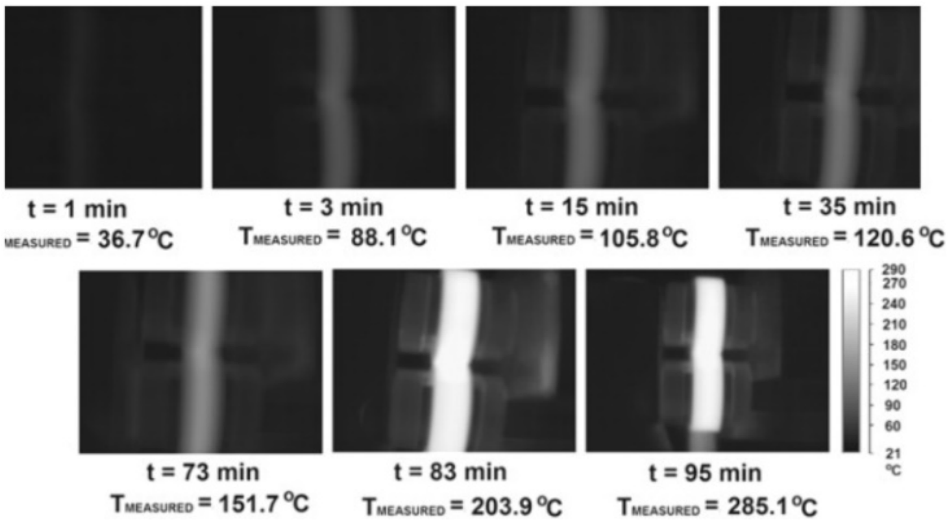


Figure 20. Temperature-dependent time of pure PEEK disks.

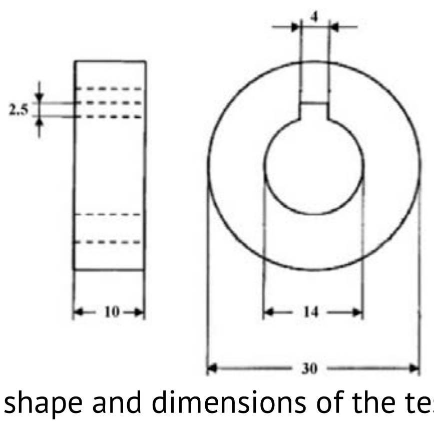


Figure 21. The shape and dimensions of the tested discs from PA46.

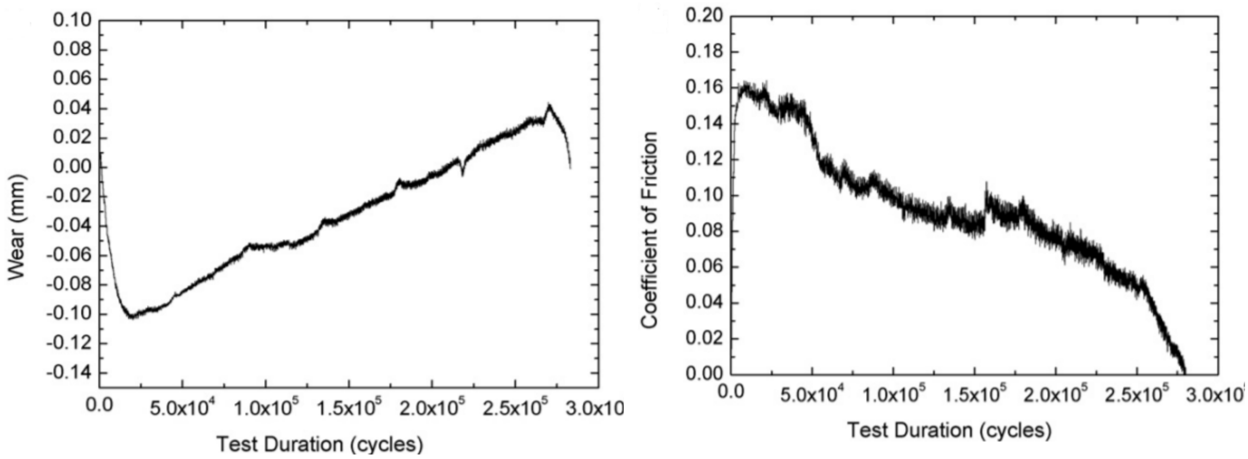


Figure 22. a) Wear of PA46+15% aramid fibers at 1500rpm; slip ratio 2%; load 400 N b) Friction coefficient of PA46 + 15% aramid fibers (1500 rpm; 2% slip ratio; 400 N load).

The research results showed that PA46 reinforced with 15% aramid fibers has higher wear than PA46 reinforced with a lower percentage of aramid fibers. Instead, PA46 reinforced with 15% aramid fibers has the lowest coefficient of friction. Weight loss through wear is generally the same for all tested materials. They found that weight loss and wear are a linear relationship for all types of PA46 materials reinforced with aramid fibers. Finally, PA 46 reinforced with aramid fibers in different proportions can be used in toothed transmissions with low moments, speeds, and pressures, [33].

2.2 Theoretical argumentation of Steel/Plastic tribological couples

Most thermoplastic polymers generate a film transfer on the metal surface, which helps to reduce the wear and the coefficient of friction of the materials, (Figure 23a). However, at a high-level interface temperature plastic deformation occurs which damages the soft surface leading to large damage. Reinforcement of thermoplastic materials will help reduce the wear rate, and to obtain good friction for applications with gears, (Figure 23b).

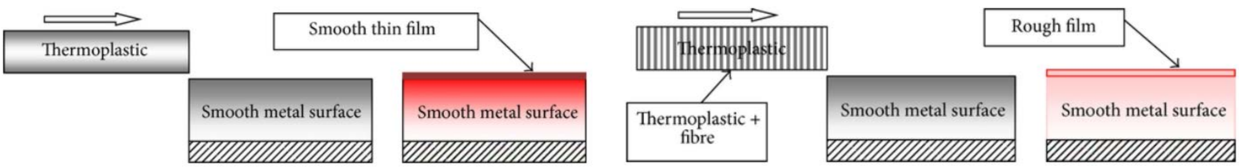


Figure 23. Possibility of film transfer on the metal counter face: a) pure thermoplastics b) composite thermoplastics reinforced with fiber, [34].

An extensive damage study was conducted by Senthilevan and R. Gnanamoorthy [35] on PA66-driven wheel reinforced by glass fibers or carbon fibers and unreinforced, paired by steel pinion (SS316). They performed research at speeds of 1000 RPM and moments from 1.5 to 3 Nm. They established differences of wear between the PA66 reinforced glass fiber and PA66 unreinforced. In the unreinforced ones, the wear is uneven due to the fact that the glass fibers have better adhesion in the matrix. After reducing the thickness of the teeth by 33%, the gear gripped. Wheel wear of PA 66 is due to scraping of the teeth of the opposite steel pinion, (Figure 24). Wear also occurs due to the low thermal resistance of the base material (PA66). In the case of the (PA66) gear wheel reinforced with carbon fibers, no such large deformations of the teeth are observed due to the high rigidity and good thermal resistance of the material.

S. Senthilvelan in [36] mentioned that (PA6) reinforced with glass fibers shows high performances related to mechanical rigidity and thermal deformation. The performance of PA6 gears is only influenced by speed and high torque. Cracks of the teeth root appeared at a pressure of 8 MPa.

Figure 24. Reduction of the thickness of the polymeric tooth due to scraping of the opposite steel wheel, [35].

Tribological research on the SS316/ PA66 gear wear reinforced with 20% fiberglass or 20% carbon fiber were made by S. Senthilvelan and R. Gnanamoorthy [37]. In these experiments they used: constant rotation speed of 1000 rpm, 1,5 till 3 Nm moments, and the pressure on the tooth calculated according to the LEWIS equation [38] from 15 till 30 MPa. Several methods have been undertaken to determine wear on plastic wheel: weight measurement before and after the running cycle, temperature monitoring during running, use of the electron microscope to analyze rolling damage. The tests were performed until the complete deterioration of the wheel from PA66 approx. up to 5 mln. rotations. The test results were integrated in the two-dimensional graphs in Figures 25, 26, 27.

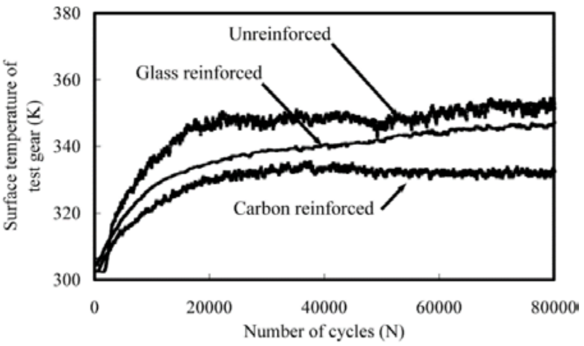


Figure 25. Gear temperature measured during running, pressure on the tooth 25 MPa, [37].

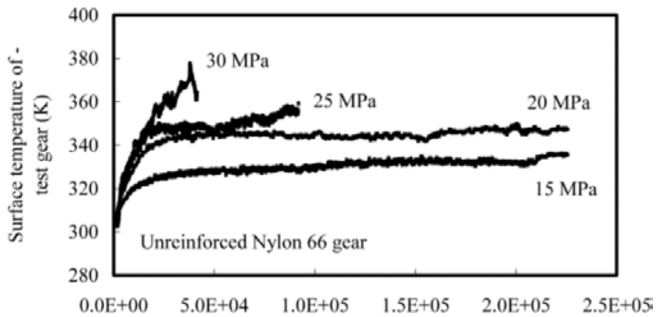
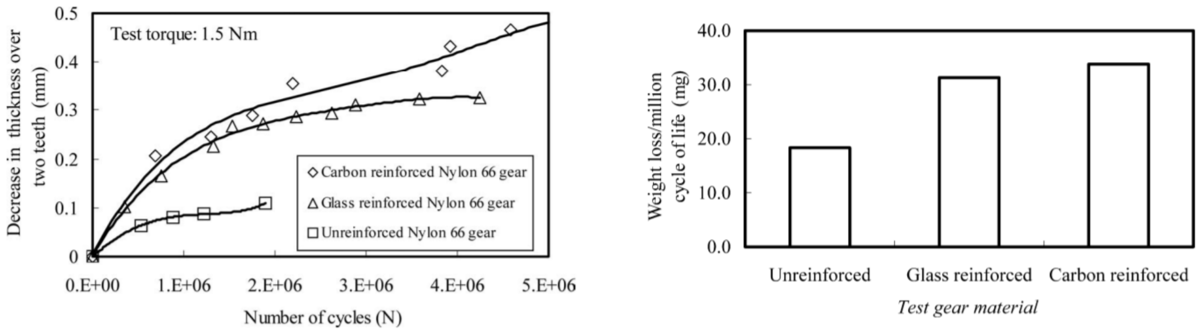


Figure 26. Temperatures in the steel gear / PA66 unreinforced with different pressures on the tooth, [37]



a) b)

Figure 27. Wear resistance of gears subjected to a bending stress of 15 MPa on tooth: a) Decrease in tooth thickness; b) The weight loss of PA66 reinforced wheel and unreinforced / million cycles, [31].

In the conclusions they mentioned that the wear depends on the type of reinforcement of the basic resine and on the orientation of the fibers, in the running direction the wheel wears less and the placement of the fibers perpendicular to the running direction the wheel wears more. Reinforced wheels have much less wear than unreinforced ones.

2.2 Theoretical argumentation of Plastic/Steel tribological couples

H. Duzcukoglu [39] did experiments on plastic/steel gear tribological couples. The main scope was to reduce the running temperature and improving heat transfer. He observed that this aim can be obtain by drilling holes in the body of the plastic teeth. The pinion made by PA6 (lubricated with oil during running) and the driven wheel from AISI 8620 (equivalent EN 20NiCrMo2) hardened and cooled in oil to a hardness of 56 HRC, Table 3. Active zones of teeth was polishing at Ra=0,6…0,8μm surface roughness. The PA6 pinion was made by 2 modes: solid one Figure 28, and drilling holes in the body of the plastic teeth (Figures 29, 30), [39].

Table 3

Properties of materials used in the tests, [39]

	Polyamide 6	AISI 8620
Density (gr/cm^3)	1.135	7.85
Tensile modulus of elasticity (N/mm^2)	3000	205.000
Thermal conductivity (W/Km)	0.28	46.6
Poisson`s ratio	0.41	0.3
Hardness	M80	56 HRC
Tensile strength, yield (N/mm^2)	70	560

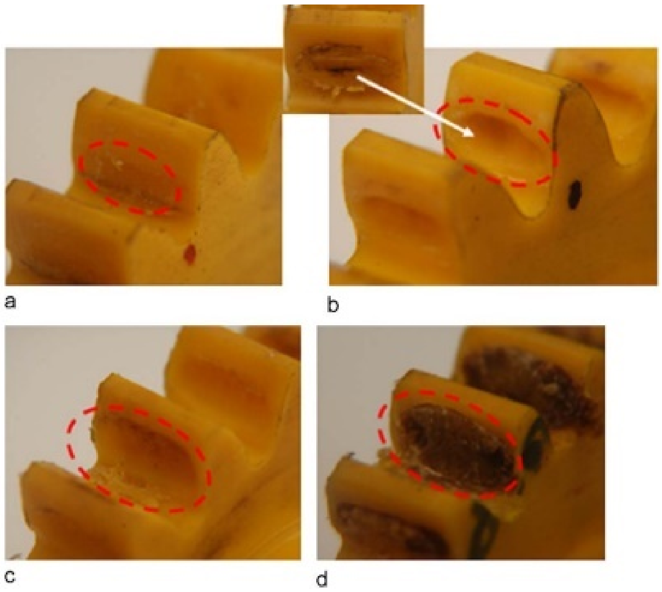


Figure 28. Damage of the gear wheel teeth (without holes) at moments:
a) 6,12 Nm, b) 10,32 Nm, c) 16,53 Nm, d) 23,3 Nm.

Considerable performance of the drilled gear was observed. This can be explained by the fact that the holes in the tooth have absorbed the deformation of the material, hysterical heat loss was did by the orifices in the teeth. Cooling holes on the tooth body absorb deformation energy, lowering running temperatures. As the torque increased by 23.3 Nm, the temperature at the gear surface increased for a certain period of time to 100^{0}C and then reached a thermal equilibrium of 84^{0}C.

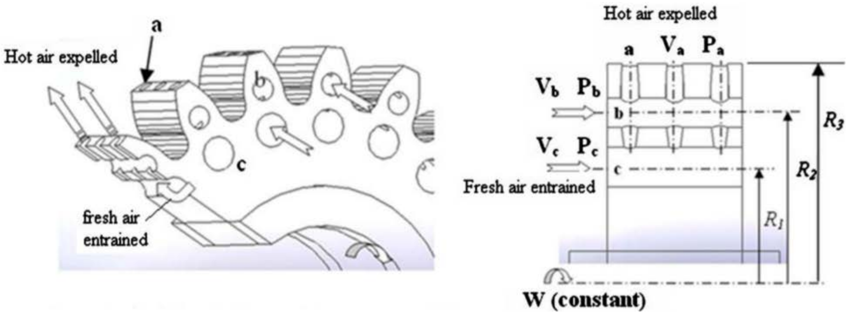


Figure 29. View of the gear provided with cooling holes.

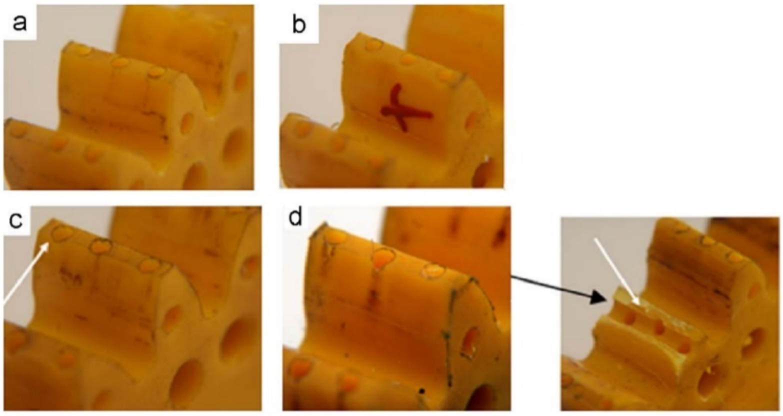


Figure 30. Damage of the gear wheel teeth provided with holes at moments:
a) 6,12 Nm, b) 10,32 Nm, c) 16,53 Nm, d) 23,3 Nm.

Teeth breakage was observed on two of the eight gears used in the experiment, due to the larger diameters of the cooling holes, which decreased the strength of the tooth and led to its breakage due to the bending stress, (Figure 30 d).

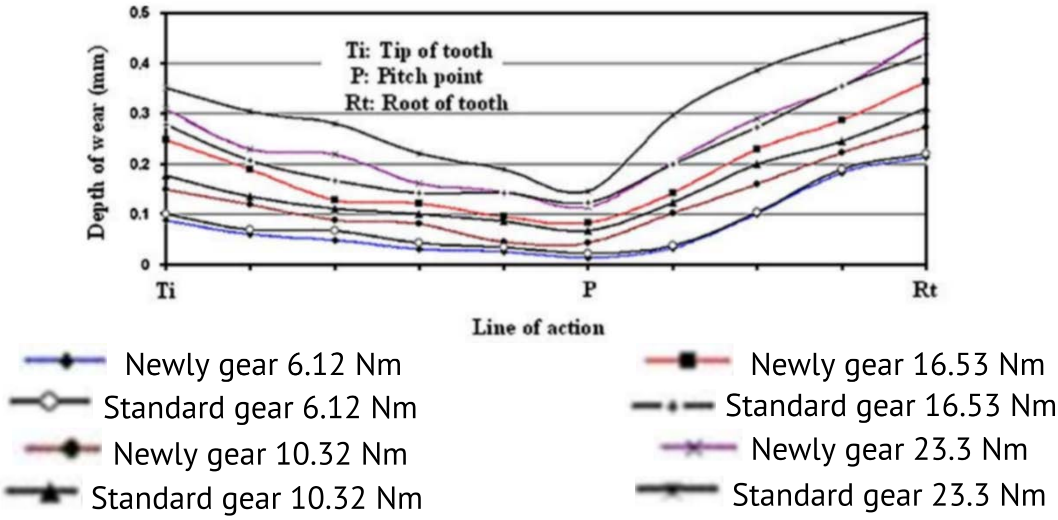
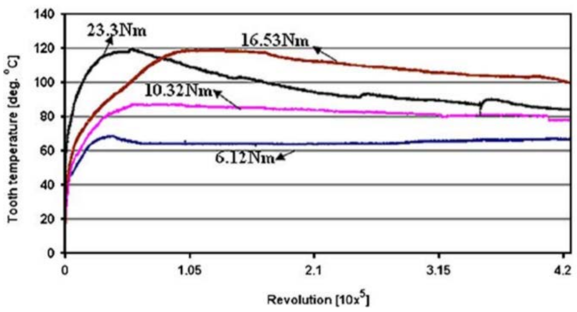
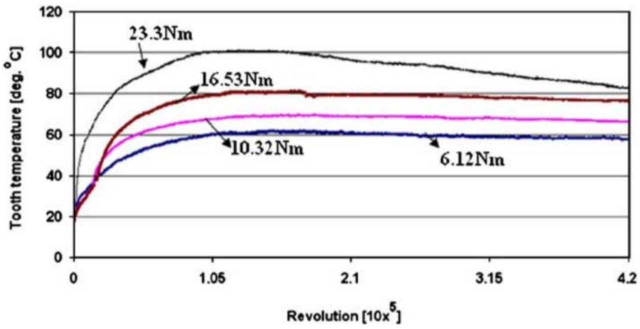


Figure 31. Wear of solid and perforated PA6 gears.

Figure 31, [39], shows the wear profiles of the teeth of solid and perforated wheels made from PA6 geared with steel wheel in the oil bath at different moments. The authors obtained following conclusions:
- was observed more wear on the root of teeth (Rt).
- low thermal conductivity of solid PA6 polyamide
- at torques greater than 9 Nm - melting and detachment of large particles from the active flank of the tooth occurs



a)



b)

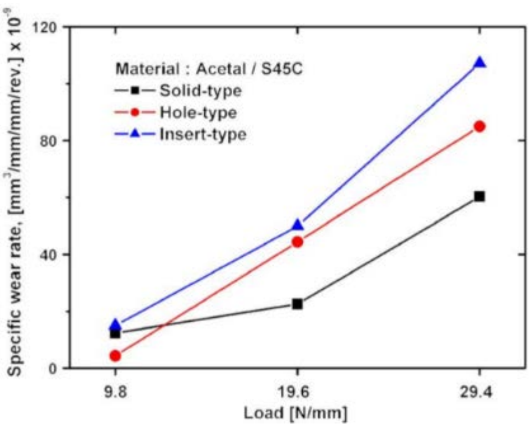
Figure 32. a) Running temperature of solid PA6 /Steel gear
b) Running temperature of perforated PA6/Steel gear.

- the highest temperature in the active zone of teeth from PA6,
- loss of mechanical properties due to high temperature, extensive tooth wear.
- When the temperature suddenly rises, the sprocket teeth break.
- Cooling holes in the body of the tooth delayed damage by increasing heat transfer, the teeth were broken on the wheels with cooling holes at loads higher than 23 Nm, this failure did not occur due to melting at the flank of the tooth but occurred due to the concentration of stresses around the cooling holes.

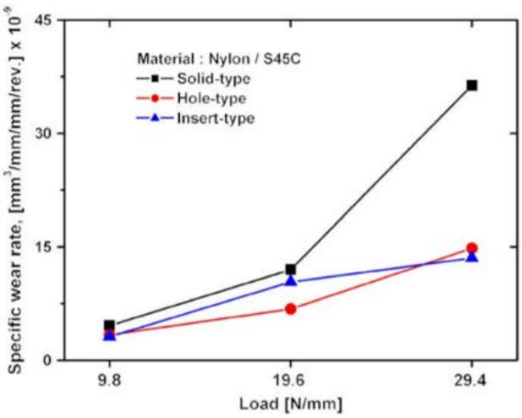
One of the most important problems of polyamide gears are high loads and sliding speeds that generate heat and damage the running surfaces of the teeth.

Similar research was done by Choong Hyun Kim [40]. The pinion from POM and PA66 were designed in 3 ways: the solid tooth, the perforated tooth, the hole provided with a steel pin, (Figure 33).

Figure 33. Wear at different pinions, [40].



a)



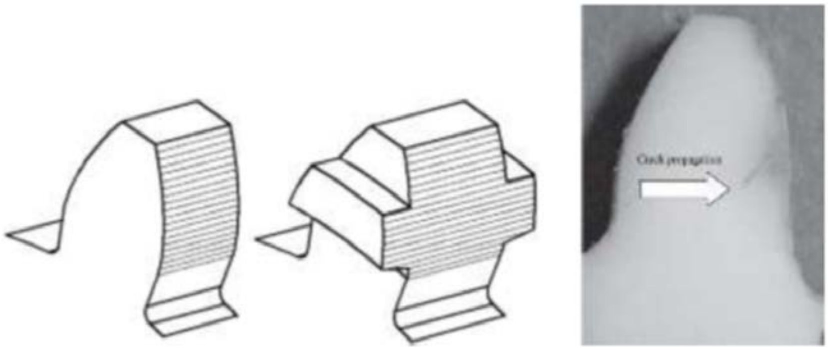
b)

Figure 34. a) Specific wear of POM / S45C gears at different moments;
b) Specific wear of PA6 / S45C gears at different moments, [40].

Choong Hyun Kim's results have been controversial:
-The running temperature has decreased in the gear with the pinion from PA66 provided with steel pins with 3−10⁰C. Was reduced the wear rate by more than 30% and increased the service life to 415%.

Choong Hyun Kim's recommended to completely avoid pairing the POM sprocket and the steel driven wheel.

H. Imrek [41] conducted research on reducing the wear of gears from PA6 by changing the shape of the teeth. The shape of the tooth was modified (Figure 35b) by increasing the area of the functional flank of the tooth, [41].



a) b) c)

Figure 35. The tooth profiles. The arrow indicates the propagation of the crack:
a) Unmodified; b) Modified; c) Crack on the flank of the tooth.

By increasing the area of the functional flank of the tooth the wear ratio decreased and the operating temperature increased. Cracks appeared on the active side of the unmodified teeth (Figure 34c), but on the modified ones the wear highlighted by the displacement of the material following the increase of the temperature appeared at the root of the teeth. H. Imrek concluded that gears with modified teeth, (Figure 35b) from PA6 have a much longer life cycle than unmodified ones (Figure 35 a) due to the lower wear coefficient, figure 36. Modified PA6 gear wheels can be used successfully in both Steel / PA6 and PA6 / Steel tribological couples.

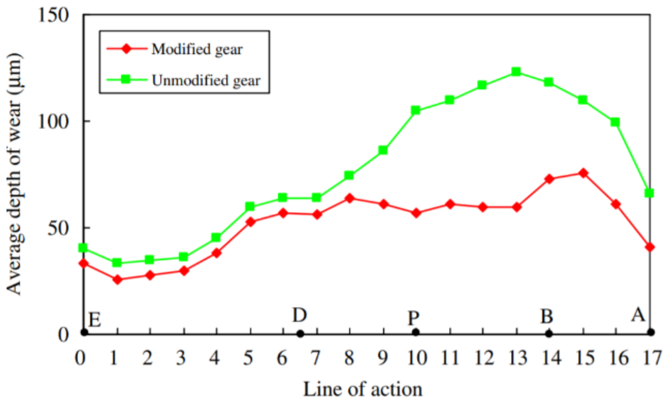


Figure 36. PA6 gear wheel wear with solid shape and modified at the moment of 8.82 Nm.

N. A. Wright and S. N. Kukureka, [42] studied experimentally and developed the technique of measuring tooth wear using the calculation of the weight of the gear wheel before the rolling cycle and after, thus determining the degree of wear. The changes in tooth shape after running experiments was observed under a microscope.

They used in their conformist experiments, real gears, made from the different materials, table 4, and non-conformist, polymer pin on steel rotating disc and simulation on rolling / sliding device with two discs, made from materials in Table 5. In all experiments they used the tribological couples Steel / Plastic and vice versa Plastic / Steel.

Table 4

Materials used in the conformist experiments

Materials used for test gears[a]			
Material designation	**Matrix**	**Reinforcement**	**Lubricant**
RF1006	PA66	30% Short glass fibres	
RFL4036	PA66	30% Short glass fibres	15 % PTFE
RC1006	PA66	30% Short carbon fibres	
RCL4036	PA66	30% Short carbon fibres	15 % PTFE
Verton	PA66	30% Long glass fibres	

Table 5

Wear material by non-conformist method, [42]

Wear factor values as supplied by LNP Plastics (1995b)	
Material	**Wear factor (K)**
2 K PA66 (skin material)	200
RF1006	75
RFL4036	16
RC1006	18
RCL4036	10
2 K PA + PTFE[a] (skin material)	12
Verton[b]	75
[a]Values for RL4040 (PA66 + 20% PTFE)	
[b]Values for RF1006.	

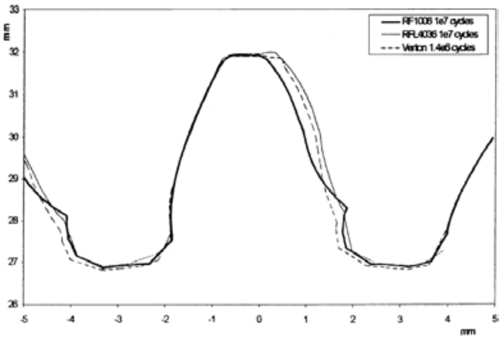


Figure 37. PA66 30 GF / SFG (RF 1006) gear tooth wear, PA 66 30 GF 15PTFE / SFG (RFL 4036), PA66 30 GF-LFG (VERTON) in gear with steel pinion.

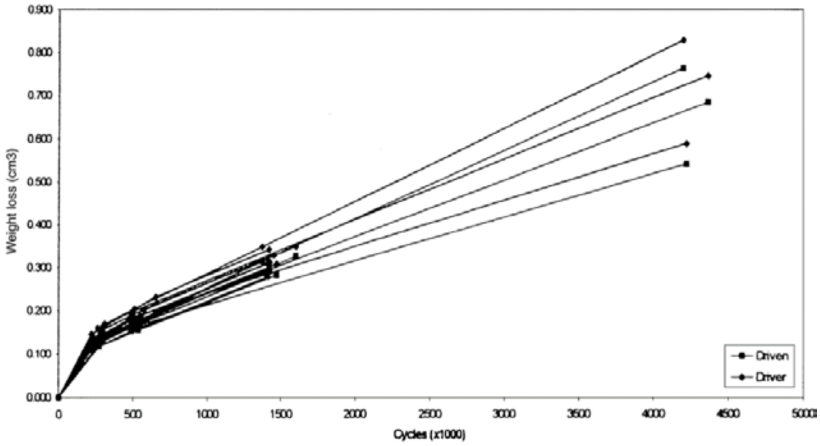


Figure 38. The PA66 30 GF gear wheel wear, [42].

N. A. Wright and S. N. Kukureka [42] mentioned that (PA 66) absorbs a significant amount of water so it is recommended to place this gear in a sealed box. By the non-conformist method they found out that PA66 30GF 15 PTFE (with short glass fibers) and PA66 20 PTFE have the lowest wear coefficient, (Table 5). The minimal and uniform wear of the tooth flank has gear wheel made from PA66 30GF 15 PTFE (with short glass fibers), (Figure 37). It is also recommended to use PA66 30 GF gears as driven wheels to achieve a lower wear coefficient. Obtained wear ratio by conformist and nonconformist tests they introduced in Figure 38.

They concluded that PA66 30GF 15 PTFE gear wheel can be used brilliantly in pair with steel gear wheel because of the lower wear compared to other materials used in their tests.

Many defects occur due to material erosion, high moments and insufficient heat transfer. In order to optimize the wear of the plastic gear, the following parameters must be taken into account; moment, ambient temperature, tooth contact temperature, running speed, running medium (acids, bases, space, petrochemistry).

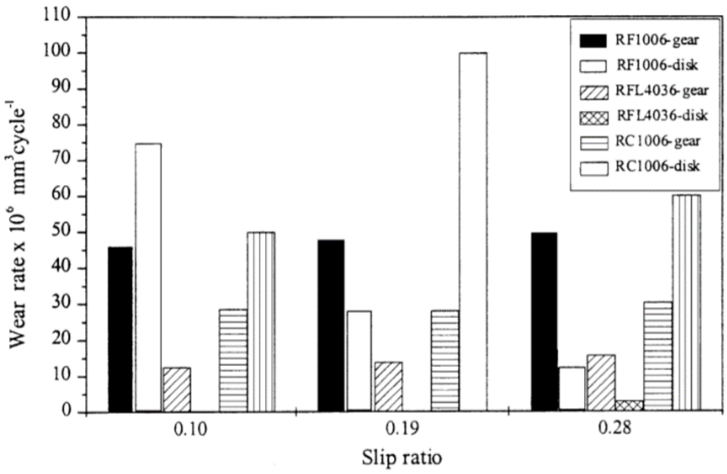


Figure 39. Comparison of wear rates, [42].

Conclusions

In this article was studied the tribological pairs Plastic / Plastic, Steel / Plastic, Plastic / Steel for classic gears. The main goal is to find the best compatible tribological pairs for precessional transmission, where more than two pairs of teeth can be in contact. Compared to the classical gears in precessional transmissions the torque is distributed on several teeth at the same time. Thus, from a theoretical point of view in the precessional transmission it is possible to use the same tribological couplings as for classical gears.

Following the study, it was established:

1.The steel gear wheel can be produced from ***40Cr10, X5CrNiMo17, 20NiCrMo2, C45E*** because are much less deformed by heat treatment than carbon steels, this conclusion being of great importance for small and precise parts whose further hardening processing is difficult and sometimes impossible due to their small size.

2. Based on experimental research conducted by scientists around the world, the most commonly used basic resins with pure crystalline structure used in the manufacture of gears are highlighted: unsaturated polyester resins ***(PA6 și PA66),*** polyacetals *(POM),* polyphenylene sulfide ***(PPS)***, polyether ether ketone ***(PEEK)*** and polybenzimidazole ***(PBI)*** materials which are used in the pure and composite states (reinforced with fibers, fillers, lubricants, etc.). Fillers, fibers, and additives are substances added in low concentrations in polymers to improve (from 30% to 40%) physical, chemical, electrical properties, to facilitate production or to change these properties.

3. Compared to metal gears, the thermoplastic pinion and driven gear wheel can be made from same material ***PA6/PA6, POM/POM*** with transmission torques around 10 Nm.

4. For the ***PA66 30GF 15PTFE/ PA66 30GF 15PTFE*** pairs, the wear is higher but can be transmitted torques up to 10 Nm short period of time.

5. The longest-lived pair with lowers friction coefficient (μ=0.22) is ***PA66 30GF 15PTFE2Si / POM 20PTFE.***

6. The applications of ***PTFE*** lubricant in the pure polyamide matrix (***PA)*** reflect a low coefficient of friction. As a result, the gear operates at lower temperatures.

7. The use of the combination ***PTFE-POM*** does not significantly improve the tribological performance of the gear.

8. The coefficient of friction is determined on the basis of temperature measurements. The exact determination of the temperature in the gear optimizes the design of the gears.

9. Fiberglass-reinforced polymers significantly increase durability at high torques.

10. The transmission torque decreases more slowly in the unreinforced pairs than the reinforced ones.

11. At the higher number of cycles (10^7) it is necessary to check whether it is not better to apply unreinforced materials.

11. In ***SS316/ PA66*** (reinforced by glass fibers or carbon fibers and pure state) was highlighted that in the unreinforced ones, the wear is uneven due to the fact that the glass fibers have better adhesion in the matrix.

12. In the case of the ***(PA66)*** gear wheel reinforced with carbon fibers, no such large deformations of the teeth are observed due to the high rigidity and good thermal resistance of the material.

13. Thermal conductivity is better to fiberglass-reinforced gears.

14. The wear depends on the type of reinforcement of the basic resin and on the orientation of the fibers, in the running direction the wheel wears less and the orientation of the fibers perpendicular to the running direction the wheel wears more.

15. Reinforced gear wheels have much less wear than unreinforced ones.

16. To reduce the running temperature and improving heat transfer can be drill the teeth of the PA6 gear wheel, (as shown in Figure 29). The „cooling holes" on the tooth body absorb deformation energy and lowering running temperatures. More attention should be paid to the position and size of the cooling holes.

17. To reduce the running temperature and improving heat transfer the cooling holes can be provided with steel pins. By this way was obtained significantly improvements: running temperature has decreased in the gear with the pinion from PA66 provided with steel pins with 3...10^{0}C. Was reduced the wear rate by more than 30% and increased the service life to 415%.

18. By increasing the area of the functional flank of the tooth the wear ratio decreased and the running temperature increased, (Figure 35 b). Modified PA6 gear wheels can be used successfully in both Steel / PA6 and PA6 / Steel tribological couples.

19. N. A. Wright and S. N. Kukureka mentioned that (PA 66) absorbs a significant amount of water, so it is recommended to place it in sealed box.

20. The minimal and uniform wear of the tooth flank has gear wheel made from ***PA66 30GF 15 PTFE*** (with short glass fibers), (Figure 37). It is also recommended to use ***PA66 30 GF*** gears as driven wheel to achieve a lower wear coefficient.

Many defects occur due to material erosion, high moments and insufficient heat transfer. In order to optimize the wear of the plastic gear, the following parameters must be taken into account; torque, ambient temperature, tooth contact temperature, running speed, running medium (acids, bases, space, petrochemistry).

The results of the studies made have major differences but virtually all researchers mention that the primary influence on polymer gears has temperature and time of use, two factors that contribute to wear. One the other hand the most important problems of polyamide gears are high loads and sliding speeds that generate heat and damage the running surfaces of the teeth.

There is a wide range of plastics, but they have limited information on mechanical and tribological properties, so it is necessary to test the gear pairs to find out the tribological performance of the gear. It is recommended to do a comprehensive study for such materials It is important to research the wear of thermoplastics and their thermal resistance. The addition of thermoplastic reinforcing materials helps to harden the surface, which will improve the tribological behavior of the polymer. This reduces wear and decreases the coefficient of friction in dry conditions. And in conditions of lubrication, contradictory work takes place and further investigations are needed.

Therefore, it is not possible to make a universal gear for all possible types of applications, it is necessary to identify the purposes of the gear:

- Identifying the purpose of the gear (torque, impact, rigidity);
- Thermal (temperature range and maximum operating temperature, etc.);
- Ambient (cosmos, water, humidity and air temperature, etc.);
- Identifying the chemical environment
- Defining the demands of the chemicals,
- Temperature,
- Contact time;
- Identification of specific requirements
- UV actuation, opaque or transparent, resistance to fatigue and deformation under the continuous application of forces;
- Definition of manufacturing processes: injection molding, hot / cold pressing, extrusion.
- Assembly, plating, adhesion, welding, etc.
- Availability and accessibility of thermoplastic material.

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References

1. Bostan I. *Precessional Transmissions. Synthesis, Kinematics and Calculation Elements*. Volume I. Chişinău: Bons Offices, 2019, 477 p. ISBN 978-9975-87-495-3. (in romanian)
2. Bostan I. *Precessional Transissions. Contact Geometry, Surface Generation and Applications*. Volume II. Chişinău: Bons Offices, 2019, 593 p. ISBN 978-9975-87-525-7. (in romanian)
3. Traian D. *Fine mechanical construction elements*. Didactic and pedagogical publishing house, Bucharest 1980, pp. 73 – 82. (in romanian)
4. David R. T. Roberts, Simon James Holder. Mechanochromic systems for the detection of stress, strain and deformation in polymeric materials. In: *Journal of Materials Chemistry* , 2011, 21(23):8256-8268; DOI:10.1039/C0JM04237D
5. Valeriu V. Jinescu. *Physical properties and thermomechanics of plastics*. Volume II. Bucharest: Technical Publishing House, 1979, pp. 13 - 34.

6. Poole R. J. The Deborah and Weissenberg numbers. In: *Rheology Bulletin,* 2012, 53 (2) pp. 32 – 39.
7. https://www.ensingerplastics.com/en/shapes/engineering-solutions/mechanical-properties
8. Yunhua L. Isotropized Voigt-Reuss model for prediction of elastic properties of particulate composites. In: *Mechanics of Advanced Materials and Structures*, 2021, pp. 1 – 13. https://doi.org/10.1080/15376494.2021.1913772
9. Mort L. *Machine Elements in Mechanical Design*: Pearson Education South Asia Pte Ltd, (2006).
10. Milani A.S., Shanian A., Lynam C., Scarinci T. An application of the analytic network process in multiple criteria material selection. In: *Material and Design*, 2013, 44 pp. 622 – 632, doi:10.1016 /j.mat-des.2012.07.057.
11. Verein Deutscher Ingenieure, VDI 2736: Part 2, Thermoplastic gear wheels, Cylindrical gears, Calculation of the load-carrying capacity, VDI-RICHTLINIEN (2014).
12. Pogačnik A. Effect of physical parameters on tribological properties of polymers for gears (in Slovenian language), phD thesis, 2013.
13. Hoskins T.J., Dearn K.D., Kukureka S.N., Walton D. Acoustic noise from polymer gears –A tribological investigation. In: *Material and Design*, 2011, 32, pp. 3509–3515, doi: 10.1016/j.matdes. 2011 02.041.
14. ISO 1328-1:2013, Cylindrical gears - ISO system of flank tolerance classification - Part 1: Definitions and allowable values of deviations relevant to flanks of gear teeth, 2013 .
15. Victrex PEEK 650 G material datasheet. https://www.victrex.com/en/datasheets (accessed 27 May 2019).
16. Thermoplastics and Thermoplastic Composites 3rd Edition-Michel Biron, ISBN: 978-0081-02-501-7 Published Date: 8th June 2018 Page Count: 1164.
17. https://www.sabic.com/assets/en/Images/Advanced%20Gear%20Solutions_tcm1010-5058.pdf;
18. Fernandes C.M.C.G., Rocha D.M.P., Martins R.C., Magalhães L., Seabra J.H.O. Finite element method model to predict bulk and flash temperatures on polymer gears, Tribol. Int. 120 (2018) 255–268, doi: 10.1016/j.triboint.2017.12.027.
19. https://www.slideshare.net/manishrdtata/1-plastic-materials
20. Hakimian E., Sulong A.B. Analysis of warpage and shrinkage properties of injection-molded micro gears polymer composites using numerical simulations assisted by the Taguchi method, Mater. Des. 42 (2012) 62–71, doi: 10.1016/j.matdes. 2012.04.058.
21. Kurokawa M., Uchiyama Y., Nagai S. Performance of plastic gear made of carbon fiber reinforced poly-ether-ether-ketone, Tribol. Int. 32 (1999) 491–497,: 10.1016/S0301- 679X(99)0 0 078-X. PEEK
22. Kurokawa M., Uchiyama Y., Nagai S. Performance of plastic gear made of carbon fiber reinforced poly-ether-ethe-ketone: part 2, Tribol. Int. 33 (20 0 0) 715–721, doi 10.1016/S0 301-679X(0 0)0 0111-0.
23. M. Kalin, M. Zalaznik, S. Novak, Wear and friction behaviour of poly-ether-ether-ketone (PEEK) filled with graphene, WS 2 and CNT nanoparticles, Wear 332–333 (2015) 855–862, doi: 10.1016/j.wear.2014.12.036.
24. https://www.mcam.com/en/products
25. Elmquist J. L. Deciding When to Go Plastic. *Gear Technology*. 46 - 47 (2014).
26. VDI 2736: 2013-2, Thermoplastische Zahnräder, Stirnradgetriebe, Tragfähigkeits-Berechnung, VDI Riehtlinien, VDI-Verlag GmbH, Duesseldorf (2014).
27. Mao K., Li W., Hooke C. J., and Walton D. "Friction and wear behaviour of acetal and nylon gears," *Wear,* 267, pp. 639-645, 6/15/ (2009).]
28. Li W., Wood A., Weidig R., and Mao K. An investigation on the wear behaviour of dissimilar polymer gear engagements, *Wear,* 271, pp. 2176 - 2183, Jul 29 (2011)
29. Suciu V., Suciu M. V. Study of Materials" Bucharest, Fair Partners, 2007- 251 pages; ISBN 978-973-1877-01-3
30. Mao K., Langlois P., Hu Z., Alharbi K., Xu X., Milson M., et al. "The wear and thermal mechanical contact behaviour of machine cut polymer gears," *Wear,* 332–333, pp. 822-826, 5// (2015).
31. Jože TAVCAR, Gašper GRKMAN and Jože DUHOVNIK [Accelerated lifetime testing of reinforced polymer gears, 19 December 2017
32. Hoskins T.J., Dearn K.D., Chen Y.K., and Kukureka S.N., The wear of PEEK in rolling-sliding contact – simulation of polymer gear applications, Wear, Vol. 309, No. 1–2 (2014), pp. 35–42.
33. Gordon and Kukureka „The wear and friction of polyamide 46 and polyamide 46/aramid-fibre composites in sliding–rolling contact," Wear, 267 (2009), pp. 669-678
34. Aldousiri B., Shalwan A., and Chin C. W. A Review on Tribological Behaviour of Polymeric Composites and Future Reinforcements, 01 Jul 2013
35. Senthilvelan S., and Gnanamoorthy R. "Damage Mechanisms in Injection Molded Unreinforced, Glass and Carbon Reinforced Nylon 66 Spur Gears," *Applied Composite Materials,* 11, pp. 377-397, (2004)]

36. Senthilvelan S., R. Gnanamoorthy R. Effect of rotational speed on the performance of unreinforced and glass fiber reinforced Nylon 6 spur gears, In: *Materials and Design,* 2007, 28 (3), pp. 765 - 772.
37. Gnanamoorthy R. Damage Mechanisms in Injection Molded Unreinforced, Glass and Carbon Reinforced Nylon 66 Spur Gears, In: *Applied Composite Materials*, 2004, 11 (6), pp. 377 – 397.
38. Maitra G. M. *Handbook of Gear Design*, New Delhi: Tata McGraw-Hill, 1994, p. 534.
39. Duzcukoğlu H. Study on development of polyamide gears for improvement of loadcarrying capacity, In: *Tribology International,* 2009, 42 (8), pp. 1146 – 1153.
40. Kim C. H. Durability improvement method for plastic spur gears, In: *Tribology International*, 2006, 39 (11), pp. 1454 - 1461.
41. Imrek H. Performance improvement method for Nylon 6 spur gears, In: *Tribology International*, 2009, 42 (3), pp. 503 – 510.
42. Wright N. A., and Kukureka S. N. Wear testing and measurement techniques for polymer composite gears, In: *Wear*, 2001, 251, pp. 1567 - 1578.
43. Linke H., Börner J., Heß R., Röhle E., Römhild I., Senf M. (Eds.), Cylindrical gears: calculation-materials-manufacturing, Hanser, München, 2016.
44. Hasl C., Illenberger C., Oster P., Tobie T., Stahl K. Potential of oil-lubricated cylindrical plastic gears, J. Adv. Mech. Des. Syst. Manuf. 12 (2018) JAMDSM0016 –JAMDSM0016, doi: 10.1299/jamdsm.2018jamdsm0016.
45. https://www.scribd.com/document/384413954/5816067-MATERIALE-PLASTICE-doc
46. Letzelter E., Guingand M., J.-P. de Vaujany, Schlosser P. A new experimental approach for measuring thermal behaviour in the case of nylon 6/6 cylindrical gears, Polym. Test. 29
47. H. Linke, J. Börner, R. Heß, E. Röhle, I. Römhild, M. Senf (Eds.), Cylindrical gears: calculation-materials-manufacturing, Hanser, München, 2016.
48. http://web.rtpcompany.com/info/data/index.htm
49. Singh A.K., Siddhartha, P.K. Singh, Polymer spur gears behaviors under different loading conditions: a review, Proc. Inst. Mech. Eng. Part J J. Eng. Tribol. 232 (2017) 210–228, doi:10.1177/1350650117711595
50. Roda-Casanova V., Sanchez-Marin F. A. 2D finite element based approach to predict the temperature field in polymer spur gear transmissions, Mech. Mach. Theory 133 (2019) 195 - 210, doi: 10.1016/j.mechmachtheory.2018.11.019 .
51. https://matmatch.com/materials/arke0008-kepstan
52. Li G., Qi H., Zhang G., Zhao F., Wang T., Wang Q. Significant friction and wear reduction by assembling two individual PEEK composites with specific functionalities, Mater. Des. 116 (2017) 152–159, doi: 10.1016/j.matdes.2016.11.100.
53. Ramachandra S., Ovaert T. The effect of controlled surface topographical features on the unlubricated transfer and wear of PEEK, Wear 206 (1997) 94–99, doi: 10.1016/S0043- 1648(96)07354-1.
54. T.F. de Andrade, Wiebeck H., Sinatora A. Effect of surface finishing on friction and wear of Poly-Ether-Ether-Ketone (PEEK) under oil lubrication, Polímeros 26 (2016) 336–342, doi:10.1590/0104-1428.2183
55. Zhang L., Qi H., Li G., Wang D., Wang T., Wang Q., Zhang G. Significantly enhanced wear resistance of PEEK by simply filling with modified graphitic carbon nitride, Mater. Des. 129 (2017) 192–200, doi: 10.1016/j.matdes.2017.05.041.
56. Davim J.P., Cardoso R. Tribological behaviour of the composite PEEK-CF30 at dry sliding against steel using statistical techniques, Mater. Des. 27 (2006) 338–342, doi:10.1016/j.
57. https://www.aeroexpo.online/prod/mitsubishi-chemical-advanced-materials/product-170365- 20271.html
58. http://www.pbi-am.com/en/molding-technology.
59. https://pbipolymer.com/wp-content/uploads/2016/06/High-Performance-PBI-Peek-Polymer-is-Revolutionizing-Industry.pdf
60. http://qepp.matweb.com/search/DataSheet.aspx?Bassnum=P1SM02&ckck=1
61. https://www.ensingerplastics.com/en/shapes/high-performance-plastics/pps
62. Milani A .S., Shanian A., Lynam C., Scarinci T. An application of the analytic network process in multiple criteria material selection, Mater. Des. 44 (2013) 622–632, doi: 10.1016/j.mat-des.2012.07.057.
63. Miler D., Žeželj D., Loncar A., Vuckovic K., Multi-objective spur gear pair optimization focused on volume and efficiency, Mech. Mach. Theory 125 (2018) 185–195, doi: 10.1016/j.mechmachtheory.2018.03.012.
64. https://gearsolutions.com/features/a-plastic-gear-design-update/
65. https://www.scribd.com/document/384413954/5816067-MATERIALE-PLASTICE-doc
66. Jabbour T., Asmar G. Stress calculation for plastic helical gears under a real transverse contact ratio, Mech. Mach. Theory 44 (2009) 2236–2247, doi 10.1016/j.mechmachtheory.2009.07.0 03.

67. Mao K., Langlois P., Hu Z., Alharbi K., Xu X., Milson M., Li W., Hooke C.J., Chetwynd D. The wear and thermal mechanical contact behaviour of machine cut polymer gears, Wear 332–333 (2015) 822–826, doi: 10.1016/j.wear.2015.01.084.
68. Xianqiang Pei and Klaus Friedrich, Sliding wear properties of PEEK, PBI and PPP, wear 274, January 2011, DOI:10.1016/j.wear.2011.09.009
69. Kukureka S. N., Hooke C. J., Rao M., Liao P. and Chen Y. K.'The Effect of Fiber Reinforcement on the Friction and Wear of Polyamide 66 under Dry Rolling–Sliding Contact', Tribology International 32, 1999, 107–116
70. Greco A.C., Erck R., Ajayi O., Fenske G. Effect of reinforcement morphology on high-speed sliding friction and wear of PEEK polymers, 18th Int. Conf. Wear Mater. 271 (2011) 2222–2229, doi: 10.1016/j.wear.2011.01.065
71. Damijan Zorko, Simon Kulovec, Jože Duhovnik, Jože Tavcar, Durability and design parameters of a Steel/PEEK gear pair, Mechanism and Machine Theory 140 (2019) pp. 825–846
72. Berer M., Tscharnuter D., Pinter G. Dynamic mechanical response of polyetheretherketone (PEEK) exposed to cyclic loads in the high stress tensile regime, Int. J. Fatigue 80 (2015) 397–405, doi: 10.1016/j.ijfatigue.2015.06.026.
73.Abbasnezhad N., Khavandi A., Fitoussi J., Arabi H., Shirinbayan M., Tcharkhtchi A. Influence of loading conditions on the overall mechanical behavior of polyether-ether-ketone (PEEK), Int. J. Fatigue 109 (2018) 83–92, doi: 10.1016/j.ijfatigue.2017.12.010.
74. Avanzini A., Petrogalli C., Battini D., Donzella G. Influence of micro-notches on the fatigue strength and crack propagation of unfilled and short carbon fiber reinforced PEEK, Mater. Des. 139 (2018) 447–456, doi: 10.1016/j.matdes.2017.11.039.
75. Greco A.C., R. Erck, O. Ajayi, G. Fenske, Effect of reinforcement morphology on high-speed sliding friction and wear of PEEK polymers, 18th Int. Conf. Wear Mater. 271 (2011) 2222–2229, doi: 10.1016/j.wear.2011.01.065.
76. Regis M., Lanzutti A., Bracco P., Fedrizzi L. Wear behavior of medical grade PEEK and CFR PEEK under dry and bovine serum conditions, Wear 408–409 (2018) 86–95, doi: 10.1016/j.wear.2018.05.005.
77. Schroeder R., Torres F.W., Binder C., Klein A.N., J.D.B. de Mello, Failure mode in sliding wear of PEEK based composites, Wear Mater 301 (2013) 717–726, doi: 10.1016/j.wear.2012.11.055.
78. Mohammed A.S., M.I. Fareed, Improving the friction and wear of poly-ether-etherketone (PEEK) by using thin nano-composite coatings, Wear 364–365 (2016) 154–162, doi: 10.1016/j.wear.2016.07.012.
79. Pei X.-Q., Bennewitz R., Busse M., Schlarb A.K. Effects of single asperity geometry on friction and wear of PEEK, Wear 304 (2013) 109–117, doi: 10. 1016/j.wear.2013.04.032.
80. Rodriguez V, Sukumaran J., Schlarb A.K., De Baets P. Reciprocating sliding wear behaviour of PEEK-based hybrid composites, Wear 362–363 (2016) 161–169, doi: 10.1016/j.wear.2016.05.024. [10] V. Rodriguez, J. Sukumaran A.K. Schlarb P. De Baets, Influence of solid lubricants on tribological properties of polyetheretherketone (PEEK), Tribol. Int. 103 (2016) 45–57, doi: 10.1016/j.triboint.2016.06.037.
81.Shrestha R., Simsiriwong J., Shamsaei N. Mean strain effects on cyclic deformation and fatigue behavior of polyether ether ketone (PEEK), Polym. Test. 55 (2016) 69–77, doi: 10.1016/j.polymertesting.2016.08.002.
82. Shrestha R., Simsiriwong J., Shamsaei N., Moser R.D. Cyclic deformation and fatigue behavior of polyether ether ketone (PEEK), Int. J. Fatigue 82 (2016) pp. 411–427, doi: 10.1016/j.ijfatigue.2015.08.022.
83.Kurokawa M., Uchiyama Y., S. Nagai, Performance of plastic gear made of carbon fiber reinforced poly-ether-ether-ketone, In: *Tribology International,* 1999, 32 pp. 491 – 497, doi: 10.1016/S0301- 679X(99)0 0 078-X.
84. Kurokawa M., Uchiyama Y., Nagai S. Performance of plastic gear made of carbon fiber reinforced poly-ether-ether-ketone: part 2, In: *Tribology International,* 2000, 33 (10) pp. 715 – 721, doi: 10.1016/S0301-679X(0 0)0 0111-0.