

# STUDY OF WEAR RESISTANCE AND FRICTION COEFFICIENT OF POLYMERIC MATERIALS FOR METAL-POLYMER GEARS UNDER DRY FRICTION

Original scientific paper

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## Abstract:

Various types of tribotechnical polymeric materials are widely used for metal-polymer (MP) gears to ensure their reliable operation in dry sliding friction conditions. These include polyamides, polyacetals, polyetheretherketones, polyethylene terephthalate, and other polymers. The wear resistance of polyamides (PA6, PA66, PA6+30GF, PA6+30CF, PA6+MoS<sub>2</sub>, PA6+oil), polyacetals (POM-H, POM+35PTFE, POM+20PTFE, POM+60Bronze, POM+20PTFE+30Bronze; POM+10PTFE+20Bronze, POM+15PTFE+15GF, POM+10PTFE+10GF, POM+10PTFE+20Bronze+10GF, POM+10PTFE+15Bronze+5GF), polyetheretherketones (PEEK, PEEK+30GF), and polyethylene terephthalates (PET, PET+PTFE) on steel has been studied in this work. In order to determine their wear resistance and sliding friction coefficient, the authors' method of model triboexperimental studies of materials under sliding friction according to the pin-on-disk scheme was used. As a result, their wear resistance indicators were established and used to determine the wear resistance characteristics by the least squares method. They are necessary for the mathematical modeling of the wear kinetics of MP gears using the corresponding author's method. In order to compare the wear resistance of the studied polymeric materials and their compositions over an extended range of specific friction forces, graphical indicators of wear resistance (wear resistance diagrams) were constructed. On the basis of these diagrams, quantitative and qualitative regularities of the tribological behavior of the studied polymers in a tribopair with steel 45 were established. The change in the friction coefficient with increasing contact pressure was also investigated. The qualitative and quantitative parameters of this effect were determined.

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## 1. INTRODUCTION

Polyamides PA and their composites, polyacetal POM-N and its composites, and less commonly polyetheretherketone PEEK and terephthalate polyethylene PET and their composites are used in metal-polymer (MP) gears operating under dry friction conditions. Pin-on-disk tribotesters (ISO 7148-2-2023 [1]) are widely used to study the wear resistance of polymeric materials.

Studies of the wear resistance of these polymeric materials and their composites in dry conditions, in conjunction with steel, using testers of various designs are available in the literature. In particular, the results for polyamides are presented in [2-11]. In [2], the friction and wear of 18 polymers (unfilled and their composites) in a tribopair with bearing steel AISI 52100 in air and water were studied on a pin-on-disk tester. The unfilled polymers were polyamide PA66, polyacetal

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POM, polyethylene terephthalate PET, polyetheretherketone PEEK, and polyphenylene sulfide PPS. The tests were carried out under the following conditions: load  $F = 500$  N, contact pressure  $p = 5.0$  MPa, sliding speed  $v = 0.25$  m/s, contact temperature  $T_{\text{cmin}} = 50^\circ\text{C}$ , and  $T_{\text{cmax}} = 300^\circ\text{C}$ , ambient temperature  $T = 20\text{-}22^\circ\text{C}$ , relative humidity  $\text{RH} = 40\text{-}60\%$ . Polytetrafluoroethylene (PTFE) and glass fiber (GF) were used as fillers. In [3], the tribological behavior of PA6 polyamide filled with glass fiber and other tribopolymers was studied using a pin-on-disk tester. The study was conducted at  $F = 15$  N,  $v = 1, 2, 3$  m/s,  $\text{RH} = 70\%$ . Twenty-one different basic and composite polymeric materials for tribotechnical applications in mechanical engineering were studied in [4]. These were the following three groups of materials: 1) for sliding friction units; 2) for mechanically loaded units subjected to friction and wear; 3) two chemically resistant amorphous materials with special friction properties. The following conditions were chosen:  $p = 2$  MPa,  $v = 0.4$  m/s,  $T = 23^\circ\text{C}$ . The mechanical and tribological properties in dry friction of fiberglass-reinforced PA6 polyamide filled with solid lubricants such as PTFE, Graphite, and ultra-high molecular weight polyethylene (UHMW-PE) were studied in [5]. The experiments were carried out at a rotational speed of  $n = 200$  rpm and  $F = 100$  N under ambient conditions. The wear resistance of PA66+10CF+20PTFE, PA66+30GF+15PTFE, PA66+35GF, PA66+20AF, and PA66+25GF+15AF (AF - aramid fiber) and the coefficient of dry friction in the air in combination with AISI 1045 steel were determined on a pin-on-disk tester at  $p = 0.75$  MPa,  $v = 0.014$  m/s in [6]. The effect of load and sliding speed on the tribological behavior of polyamide PA6-metal during dry sliding friction, water adsorption, and electroplating on metal was studied using a pin-on-disk tribometer in [7] under the test conditions:  $F = 10 - 70$  N,  $v = 2.5 - 7.5$  m/s,  $T = 20 - 22^\circ\text{C}$ ,  $\text{RH} = 50 \pm 10\%$ . The tribological properties of PA6 over X105CrMo17 stainless steel were studied on a pin-on-disk tester under dry sliding speeds at  $p = 0.7$  MPa,  $v = 0.1, 0.5, 1.0$  m/s in [8]. The tribological behavior of a polymer composite with a PA66/PTFE matrix (80/20 wt.%) reinforced with short glass fibers in different percentages was investigated in [9]. Here, the effect of sliding speed and load on the coefficient of friction and volumetric wear under dry friction conditions was investigated using a pin-on-disk design at  $F = 20, 50$  N,  $v = 2.5$  m/s. In [10], the friction force, friction coefficients, friction temperature, and mass and volume wear were

studied in dry friction according to the ball ( $\text{Al}_2\text{O}_3$ ) - on - plate scheme (composites: cast PA6+oil, PA6+ $\text{MoS}_2$ , POM+Aluminum, PET+PTFE, PTFE+Bronze, PTFE+Graphite). Tribological tests were carried out at  $F = 10, 20, 30$  N and  $n = 450$  rpm at ambient temperature. The friction and wear of PA66+10CF composites when rubbing on steel 45C steel with grease lubrication and dry friction were compared with the properties of PA66+15GF in [11] at  $F = 120$  N,  $v = 1.0$  m/s,  $T = 25^\circ\text{C}$ ,  $n = 790$  rpm. The carbon fiber-reinforced composite demonstrated worse tribological properties when lubricated compared to the glass fiber-reinforced composite. However, the opposite was true for dry friction. The mechanical and tribological behavior of PA6+5GF+(1,2,3) graphite composites in dry friction under ambient conditions with changing speeds and loads was studied in [12]. The coefficient of friction and dry wear characteristics were evaluated under ambient conditions at  $n = 200, 400, 800$  rpm and  $F = 10, 20, \text{ and } 30$  N.

Polyacetals paired with steel in dry friction were studied in [2, 4, 13]. The authors [13] investigated the tribological behavior of POM-H, PTFE, PA66+oil, PA6+CF, and PA6+GF/Mg, taking into account the surface roughness of a 40CrMnNiMo8 stainless steel counter-sample.

In addition to polyamides and polyacetals, as an engineering class of polymeric materials for metal-polymer gears, the following are used in particular: ultra-high performance polymer PEEK and its composites (operating temperature up to  $250^\circ\text{C}$ ) and the engineering polymer PET and its composites, which exhibit slightly better tribological properties than polyamides and significantly better than polyacetals, are used for metal-polymer gears. The results of experimental studies of the tribological behavior of these polymeric materials in combination with steel are presented in [2, 4, 10, 12, 14-16]. A review of PEEK wear resistance studies is presented in [14]. It is indicated that the chemical composition, microstructure, and properties of fillers have different effects on the wear resistance of PEEK composites. The review article [15] provides some information on the results of studies of PEEK and composites based on it. Wear at dry friction on steel according to the scheme of face friction was studied in [16] for PEEK, polybenzimidazole (PBI), and polyparaffenylenes (PPP120, PPP150). Their mass wear index, the Archard wear coefficient, and contact temperature were determined depending on the  $pv$  factor at  $v = 1; 2$  m/s.

Comparison of the tribological behavior of PEEK, PEEK+10CF+10Graphite, PEEK+10CF+10Graphite+10PTFE on AISI 52100 steel under dry friction conditions in reciprocating motion was carried out in [17]. The research conditions were accepted:  $F = 6.5, 13.0, 16.0$  kN,  $p = 4, 8, 10$  MPa,  $v = 0.020, 0.050$  m/s,  $T = 25$  °C, RH = 50 %.

Studies of the wear resistance of polymeric materials in these works were conducted under different conditions (loads, sliding speeds, temperatures, air humidities), which often do not meet the requirements of ISO 7148-2 or ASTM G99-17. In particular, it is known that the ambient temperature and relative humidity have an impact on the mechanical and tribological properties of polymers, especially polyamides. As for acetals, an increase in temperature also leads to changes in these properties, but air humidity has little effect on them. Instead, polyetheretherketone and polyethylene terephthalate are characterized by a slight effect of temperature (up to 125°C and 75°C, respectively) and humidity on their mechanical properties. As for the wear resistance and friction coefficient of polymeric materials in MP tribopairs, they change very differently when the specified experimental conditions are changed according to the standardized recommendations. The temperature in the contact zone is of particular importance as a decisive factor in influencing the tribological behavior of polymeric materials. In addition, the mechanical characteristics of polymeric materials and their composites from different manufacturers may vary. Therefore, the comparison of the wear resistance of polymeric materials under different experimental conditions and obtained on various tribometers is inappropriate and not entirely accurate. Such a comparison of wear resistance would be reasonable and reliable when modeling the identity of contact conditions. The most appropriate method is to study the tribological behavior of polymeric materials according to ISO 7148-2 [1] using pin-on-disk tribotesters with controlled constant conditions, as provided in [18].

For mathematical modeling according to the author's method of the wear kinetics of metal [19-22] and MP [23-27] gears, it is necessary to determine their respective wear resistance characteristics on the basis of experimental studies of materials. It would be advisable to use the results for their wear resistance obtained under normalized external conditions for this purpose. However, the standards provide for only one level of contact pressure, and this is not sufficient to

determine the appropriate wear resistance characteristics for the specified mathematical wear model. Such studies should be conducted at several values of contact pressure while maintaining the other standardized conditions, in particular, the ambient temperature and relative humidity.

The aim of this work is to conduct model triboexperiments to establish indicators and further wear resistance characteristics of polyamides, polyacetals, polyetheretherketones, and polyethylene terephthalates. Therefore, the use of the results of studies of the wear resistance of polymeric materials at several values of contact pressures and under non-standard conditions available in the literature would be unreliable.

## 2. MATERIAL AND METHODS

The wear of the above polymeric materials under dry friction was studied using the designed, manufactured and patented pin-on-disk tribometer [18]. Here, constant ambient conditions are provided in a closed box with the studied tribopair of materials: air temperature  $T = 10-60$ °C and its relative humidity HR = 40-70%. The conditions of the experiments were chosen to correspond to ISO 7148-2: sliding speed  $v = 0.4$  m/s, contact temperature  $T_c = 23 \pm 1$ °C of polymer rod samples with a diameter of  $d = 3$  mm near the contact; relative humidity HR = 50±5%; contact pressure  $p_i = 2, 4, 6, 8$  MPa; duration of the experiment  $t = 5-10$  hours.

As a result of the study of metal-polymer material pairs, the mass wear  $\Delta M$  of two polymer samples and the average sliding friction coefficient  $f$  were determined. The wear resistance of the material in the author's phenomenological model of material wear under sliding friction [19, 20] is characterized by the indicator  $\Phi_i$ , which is the ratio of the friction path  $L_i$  to the linear wear  $h_i$  of the sample:

$$\Phi_i = L_i / h_i \quad (1)$$

where are:  $L = vt$ ,  $h_i = 4\Delta M_i / \rho \pi d^2$ ,  $\rho$  is the density,  $i = 1, 2, 3, 4$  are the steps of the nominal contact pressure  $p_i$ .

After this first stage of standard tribo-experimental studies of the wear resistance of polymeric materials for tribotechnical applications, the second target stage was implemented. Its purpose was to determine the wear resistance

characteristics  $C$  and  $m$  of polymeric materials. They are necessary for use in the author's analytical method for studying the wear kinetics of gear teeth [19, 20, 24].

Accordingly, the wear resistance indicators  $\Phi_i$  at four values of specific friction forces  $\tau_i = f_i p_i$  are approximated by the analytical wear resistance function  $\Phi_k(\tau)$  of the following type [19-21]:

$$\Phi_k(\tau) = C_k (\tau_{Sk} / \tau)^{m_k}, \quad k = 1; 2, \quad (2)$$

where are:  $C_k$  and  $m_k$  are linear and exponential characteristics of wear resistance of materials of the studied tribopair, 1 – for the steel counter disk, 2 – for the polimeric sample,  $\tau = fp$  is the specific friction force according to Amonton-Coulomb,  $\tau_s = 0.5 R_m$  is the shear strength of the polimeric materials, and  $R_m$  is their tensile strength.

The results of the approximation of the wear resistance indicators  $\Phi_i$  of the studied polymers are presented below in the form of wear resistance diagrams, and the established polymer characteristics of wear resistance  $C, m$  are given in the tables.

When modeling gear teeth wear, the wear resistance function  $\Phi_k(\tau)$  (2) unambiguously relates the wear resistance of a material to an arbitrary level of tribocontact load by the specific friction force over a significant range of its change. This cannot be achieved by using discrete values of the wear resistance indicators  $\Phi_i$  or the relative indicators of material wear resistance (wear intensity  $I_h$ , Archard's wear coefficient  $K_w$ ) available

in the literature. The wear resistance indicator  $\Phi$  is related to the linear wear intensity  $I_h$ , and to Archard's wear coefficient  $K_w$  as follows:

$$\Phi = 10^9 / I_h, \quad \Phi = 10^3 / K_w p, \quad K_w = 10^{-3} / p \Phi, \quad (3)$$

where are:  $\Phi$  (mm/mm),  $I_h$  ( $\mu\text{m}/\text{km}$ ),  $K_w$  ( $\text{mm}^3/\text{Nm}$ ),  $p$  ( $\text{N}/\text{mm}^2$ ).

### 3. RESULTS AND DISCUSSION

The results of the study of the wear resistance of polymeric materials for mechanical gears and the determination of the characteristics  $C$  and  $m$  of their wear resistance under the specified friction conditions are given in Tables 1-3. Wear resistance diagrams of polyamides, polyacetals, polyetheretherketones, and polyethylene terephthalates are shown, respectively, in Figs. 1, 2, 4, 5, and 7. There, markers also show indicators of their wear resistance  $\Phi_i$ . Material characteristics of the experimental MP tribopairs: disk 1 - normalized steel S45, 2 – polymer sample, surface roughness  $R_a = 0.8\text{-}0.9 \mu\text{m}$ , Young's modulus  $E_1 = 210000 \text{ MPa}$ , Poisson's ratio  $\nu_1 = 0.3$  (Tables 1-3).

#### 3.1 Polyamides (PA)

The characteristics of polyamides are shown in Table 1.

Wear diagrams of the studied polyamides in order of increasing wear resistance relative to unfilled PA6 are shown in Fig. 1.

**Table 1.** Tribological and mechanical characteristics of polyamides

Tribological and mechanical characteristics	Polyamides					
	PA6	PA66	PA6+30GF	PA6+MoS <sub>2</sub>	PA6+30CF	PA6+oil
$C_2 \cdot 10^6$	1.34	1.98	1.88	3.08	3.67	4.20
$m_2$	1.15	1.15	1.15	1.15	1.15	1.15
$\tau_{s2}$ , MPa	40	40	50	38	40	38
$f$	0.67-0.29	0.68-0.3	0.86-0.52	0.60-0.26	0.78-0.44	0.7-0.31
Young's modulus $E_2$ , MPa	2000	2300	2700	1660	3300	1960
Poisson's ratio $\nu_2$	0.4	0.4	0.41	0.4	0.41	0.4
Compression strength $R_m$ , MPa	80	80	100	76	80	76
Shore D hardness	75-80	80-85	80-90	70-80	80-90	70-80
Permitted contact pressure ( $p$ ), MPa	10-25	20-35	≈100	15-30	>100	15-30

Notes: The percentage volume content of the filler in the composite is indicated by numbers: 30GF - short glass fiber, 30CF - carbon fiber, MoS<sub>2</sub> - molybdenum disulfide, oil - lubricant; the range of change in sliding friction coefficients corresponds to contact pressures  $p_i = 2, 4, 6, 8 \text{ MPa}$ ; manufacturer Roechling® Sustaplast

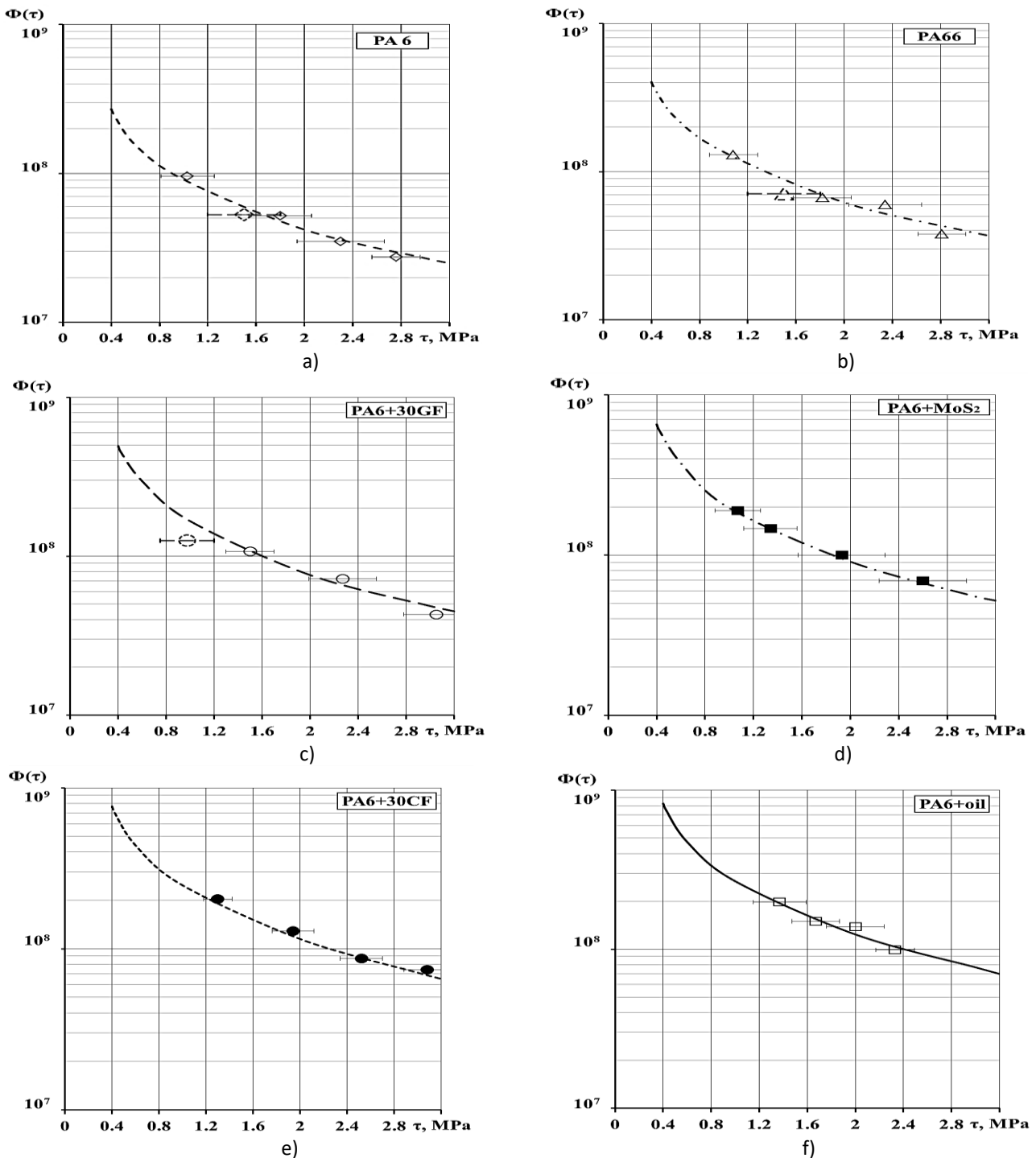


Fig. 1. Diagrams of wear resistance of polyamides: a) PA6, b) PA66, c) PA6+30GF, d) PA6+MoS<sub>2</sub>, e) PA6+30CF, f) PA6+oil

From the above diagrams of wear resistance, it is noticeable that the wear resistance indicators  $\Phi_i$  are located differently on the axis of specific force  $\tau = f\bar{p}$  since the friction coefficients are different (Table 1) at the same contact pressures. The enlarged markers in Figs. 1a, b, c show the wear resistance indicators  $\Phi$  of PA6, PA66, PA6+30GF, calculated using their wear intensity data in [28]. A good convergence of the results was established. Accordingly, the study of these polymers in a pair with steel C35 in dry friction was

carried out in accordance with ISO 7148-2 under the following conditions:  $p = 3$  MPa,  $v = 0.33$  m/s,  $T = 23 \pm 1^\circ\text{C}$ ; HR =  $50 \pm 5\%$ . There are no such data for PA6+MoS<sub>2</sub> (Fig. 1d), PA6+30CF (Fig. 1e), and PA6+oil (Fig. 1f). The wear resistance of PA6+30CF and PA6+oil is similar.

### 3.2 Polyacetals (POM)

The characteristics of polyacetals are shown in Table 2.

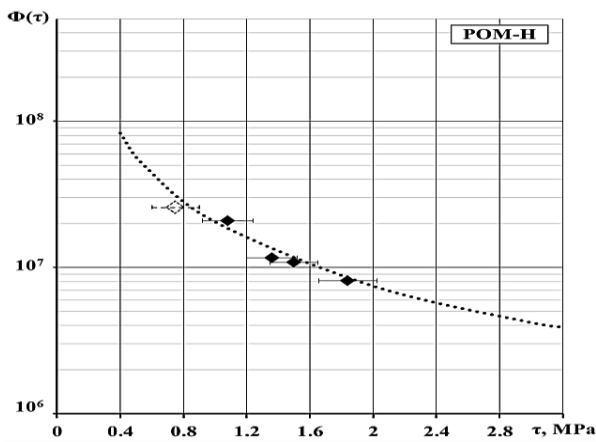
**Table 2.** Tribological and mechanical characteristics of polyacetals

Tribological and mechanical characteristics	Polyacetals				
	POM-H (homopolymer)	POM+35PTFE	POM+ 20PTFE	POM+ 60Bronze	POM+20PTFE+ 30Bronze
$C_2 \cdot 10^5$	1.12	2.27	2.27	1.80	2.85
$m_2$	1.5	1.5	1.5	1.5	1.5
$\tau_{S2}$ , MPa	33	30	31	35	35
$f$	0.54-0.23	0.46-0.2	0.45-0.2	0.61-0.31	0.64-0.32
$E_2$ , MPa	3200	3200	3300	3480	3410
$\nu_2$	0.35	0.38	0.4	0.39	0.38
$R_m$ , MPa	66	60	62	70	70
Shore hardness	85	55-65	7-25	20-40	15-35
$(\rho)$ , MPa	10-30	5-20	65-75	80-90	75-85
Tribological and mechanical characteristics	POM+10PTFE +20Br	POM+ 15PTFE+ 15GF	POM+ 10PTFE +10GF	POM+10PTFE+ 20Br+10GF	POM+ 10PTFE+15Br +5GF
$C_2 \cdot 10^5$	1.46	4.24	3.12	6.2	3.12
$m_2$	1.5	1.5	1.5	1.5	1.5
$\tau_{S2}$ , MPa	35	33	33	33	33
$f$	0.55-0.22	0.56-0.22	0.58-0.25	0.59-0.25	0.61-0.27
$E_2$ , MPa	3300	3420	3320	3450	3350
$\nu_2$	0.38	0.39	0.39	0.38	0.37
$R_m$ , MPa	70	65	66	66	66
Shore hardness	10-30	20-40	15-35	25-45	20-40
$(\rho)$ , MPa	70-80	80-90	75-85	80-90	75-85

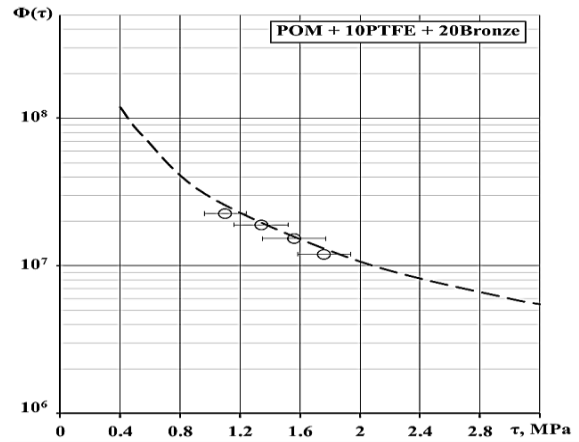
Notes: Br - Bronze (bronze powder); manufacturer Roechling® Sustaplast

Fig. 2 shows the diagrams of the wear resistance of certain types of polyacetals in order

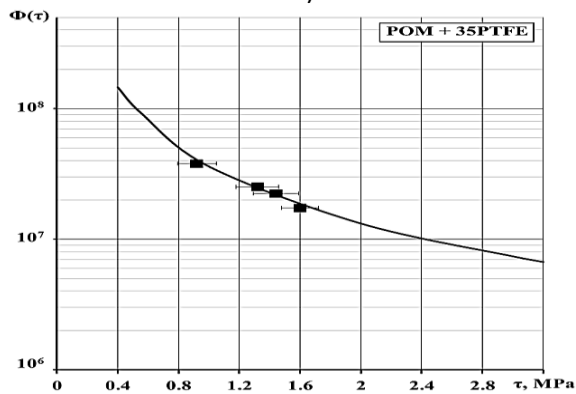
of increasing their wear resistance relative to the POM-H homopolymer.



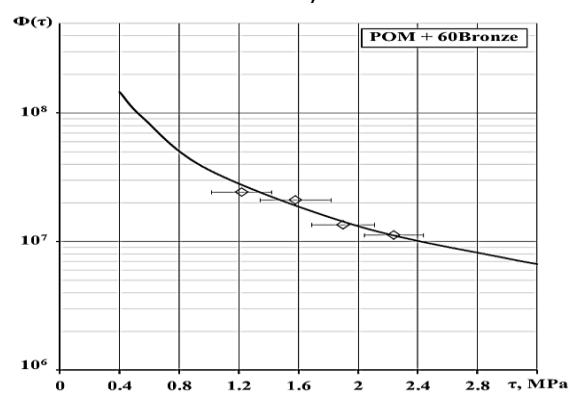
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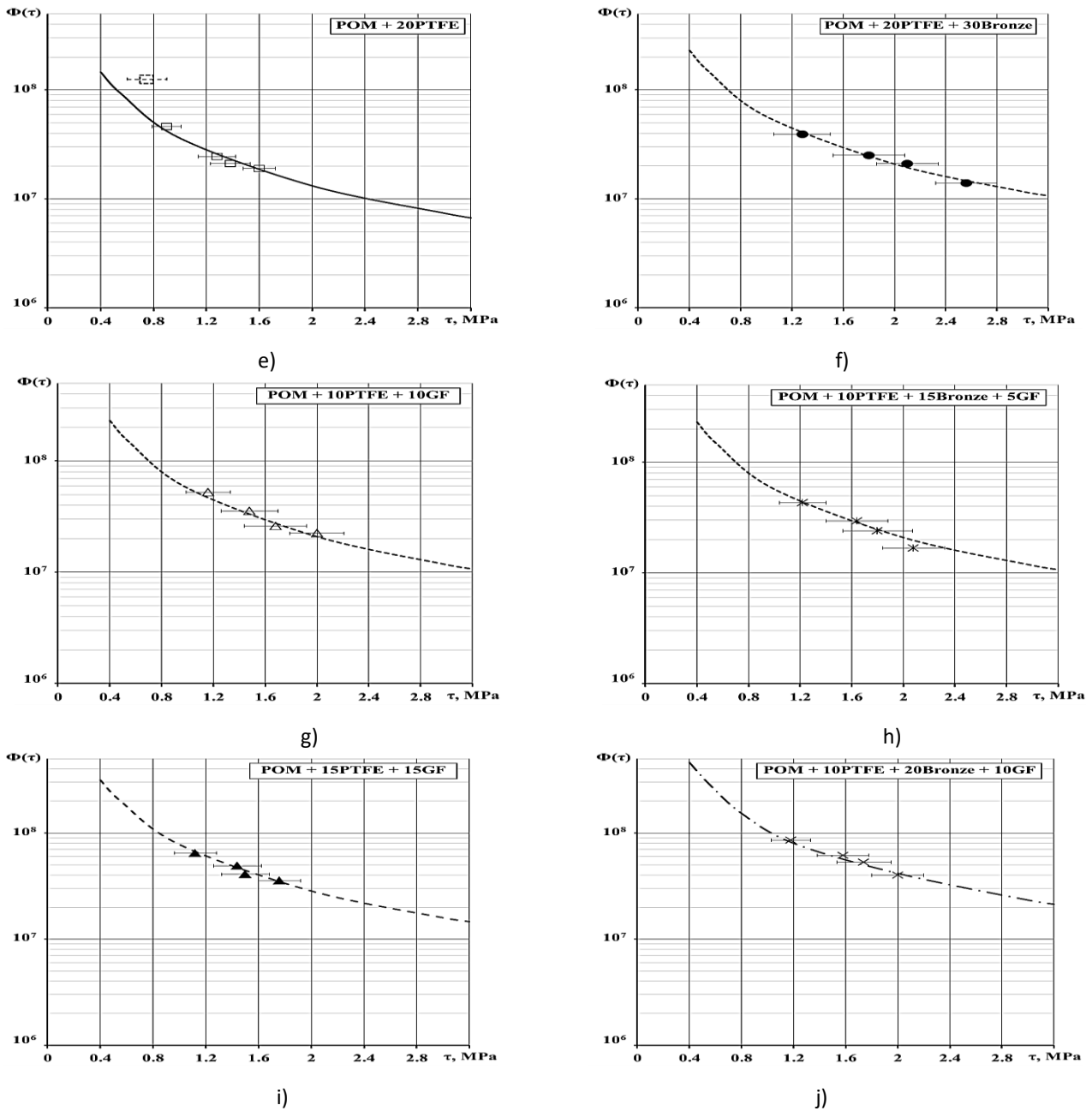
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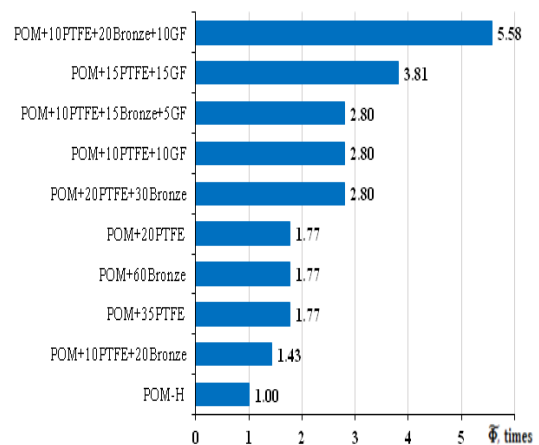
d)



**Fig. 2.** Diagrams of wear resistance of polyacetals: a) POM-H, b) POM+10PTFE+20Br, c) POM+35PTFE, d) POM+60Br, e) POM+20PTFE, f) POM+20PTFE+30Bronze, g) POM+ 10PTFE +10GF, h) POM+10PTFE+15Br+5GF, i) POM+15PTFE+15GF, j) POM+10PTFE+20Br+10GF

The enlarged markers in Figs. 2a and 2e show the wear resistance indicators of POM-H and POM+20PTFE, calculated using the data on their wear intensity from [28].

Fig. 3 shows the relative wear resistance  $\tilde{\Phi}$  of the indicated filled composites in relation to the wear resistance of polyacetal POM-H ( $\tau = 2$  MPa).



**Fig. 3.** Relative wear resistance of polyacetal composites

The fillers increase the wear resistance of the basic homopolyacetal by 1.43-5.58 times, depending on the type and composition of the components. Fiberglass in combination with PTFE and Bronze has a significant effect on the growth of wear resistance of POM+10PTFE+10GF (Fig. 2g), POM+10PTFE+5Bronze+5GF (Fig. 2h), POM+15PTFE+15GF (Fig. 2i), and POM+10PTFE+20Bronze+10GF (Fig. 2j) composites compared to POM-H in the range of 2.8-5.58 times. In the presence of PTFE, Bronze, and the absence of GF in the composition of POM+10PTFE+20Bronze (Fig. 2b) and POM+20PTFE+30Bronze (Fig. 2f) composites, their wear resistance will be 1.43-2.8 times higher, respectively. Accordingly, an increase in the content of PTFE and Bronze in the basic polymer POM-H causes an increase in wear

resistance. The wear resistance of the three composites POM+350PTFE (Fig. 2c), POM+60Bronze (Fig. 2d), and POM+20PTFE (Fig. 2e) is almost the same and slightly higher than that of the basic polymer. In the presence of PTFE and Bronze in the composition of composites and the absence of GF, their wear resistance will be 1.43-2.8 times higher, respectively. An increase in the content of Bronze and PTFE in the basic polymer POM-H leads to an increase in wear resistance.

### 3.3 Polyetheretherketones (PEEK) and Polyethylene Terephthalates (PET)

Characteristics of polyetheretherketones and polyethylene terephthalates are given in Table 3.

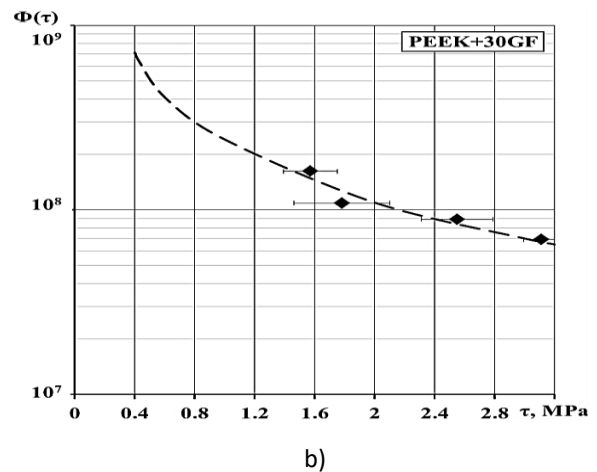
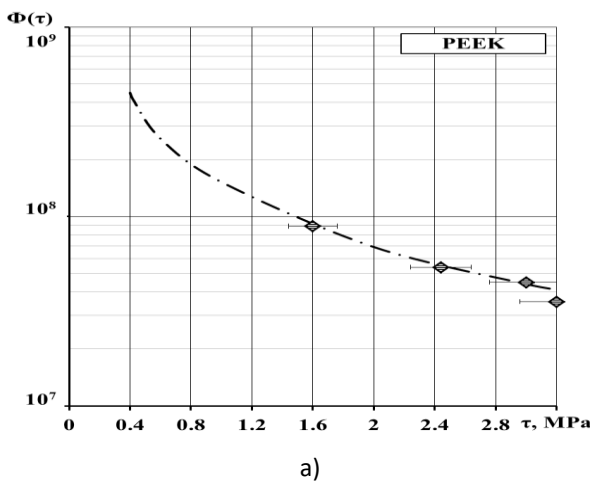
**Table 3.** Tribological and mechanical characteristics of PEEK and PET

Tribological and mechanical characteristics	Polyetheretherketones and Polyethylene terephthalates			
	PEEK	PEEK+30GF	PET	PET+PTFE
$C_2 \cdot 10^5$	17.0	15.9	39.9	71.5
$m$	1.15	1.15	1.15	1.15
$\tau_{S2}$ , MPa	50	80	40	38
$f$	0.80-0.43	0.79-0.46	0.64-0.27	0.60-0.23
$E_2$ , MPa	3400	3650	2300	2260
$\nu_2$	0.38	0.4	0.43	0.44
$R_m$ , MPa	100	160	80	76
Shore hardness	85-90	90-95	80-85	70-80
$(\rho)$ , MPa	70-100	90-150	20-30	10-25

Note: Manufacturer Roechling® Sustaplast

Figs. 4 and 5 show the diagrams of the wear resistance of polyetheretherketones and polyethylene terephthalates.

Fig. 6 shows the relative wear resistance  $\tilde{\Phi}$  of polyetheretherketones, polyethylene terephthalates, and polyamides at a specific friction force of  $\tau = 2$  MPa.



**Fig. 4.** Diagrams of wear resistance of polyesteretherketones: a) PEEK, b) PEEK+30GF

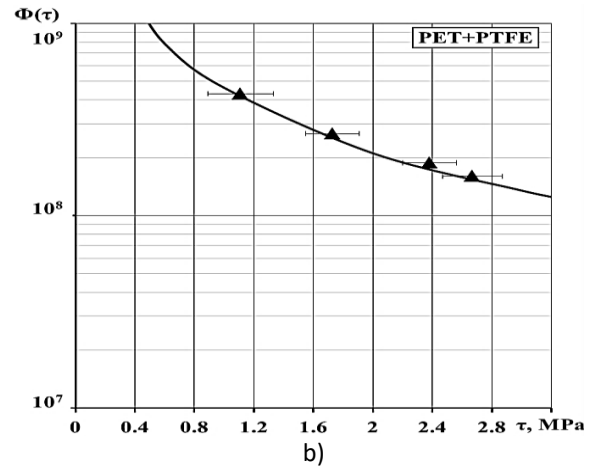
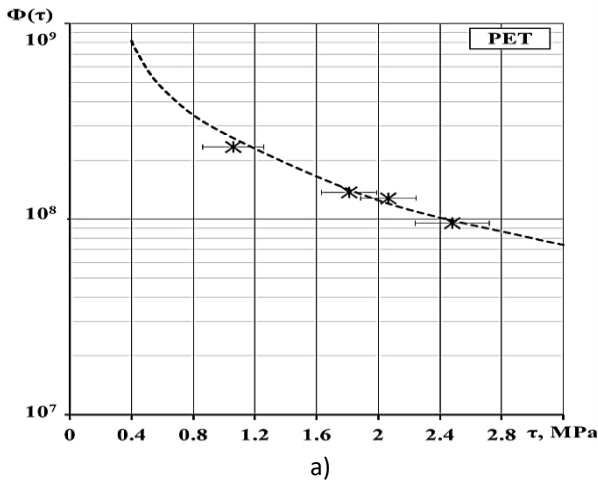


Fig. 5. Diagrams of wear resistance of polyethylene terephthalates: a) PET, b) PET+PTFE

The addition of fillers to polyetheretherketone and polyethylene terephthalate increases their wear resistance. In particular, PEEK+30GF (Fig. 4b) is 1.6 times more resistant than PEEK (Fig. 4a), and PET+PTFE (Fig. 5b) is 1.7 times more resistant than PET (Fig. 5a). Accordingly, the wear resistance of unfilled PET is 1.8 times higher than that of PEEK. Among these polymers, unfilled PEEK has the lowest wear resistance, and filled PET+PTFE has the highest.

Unfilled polyamides have lower wear resistance than PEEKs and are significantly lower than PETs and their composites. Different fillers of PA6 can increase its wear resistance by 1.81-2.95 times. The investigated PA6 polyamide composites have higher wear resistance than PEEKs. It is differentially lower to a different extent than that of PET and PET+PTFE. In particular, the PA6+oil composite is virtually identical in wear resistance to the unfilled PET.

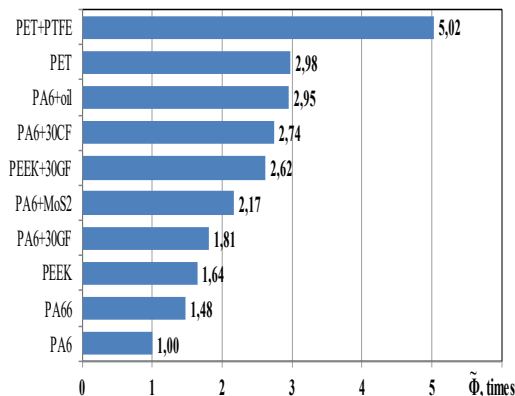


Fig. 6. Relative wear resistance of polyamides, polyetheretherketones, and polyethylene terephthalates

### 3.4 Summary Diagrams of Wear Resistance

Fig. 7 shows the diagrams of wear resistance of all studied polymeric materials for metal-polymer gears.

The wear resistance diagrams of all the tested polymeric materials shown in this summary figure provide a quick and effective comparison of their wear resistances. It is noticeable that composite No. 10 (PET+PTFE) has the highest wear resistance, and unfilled polyamide No. 11 (POM-H) has the lowest. Unfilled polymer No. 9 (PET) has the same wear resistance as the best polyamide composite - No. 6 (PA6+oil). Composites No. 5 and No. 8 (PA6+30CF and PEEK+30GF) have similar wear resistance. The next group of polymers, No. 2 (PA66), 3 (PA6+30GF), and 7 (PEEK), shows slightly lower wear resistance. Non-filled polyamide No. 1 (PA6) exhibits comparable wear resistance to the most wear-resistant composite, No. 20 (POM+10PTFE+20Bronze+10GF). In all other composites (No. 19, 12, 13, 14, 15, 16, 17, 18, 20) of POM-H polyacetal, the wear resistance is consistently increasing. However, it is significantly lower than that of even polyamide PA6, not to mention the other types of polymeric materials. Within each type of composite in each group of materials, it is also easy to establish their comparative wear resistances (see Figs. 3 and 6). When designing a gearbox, after selecting a polymer material for wear resistance, its mechanical properties, operating conditions, and cost should be considered. The final stage should be the design calculation of the transmission gear for bearing capacity, wear, and durability, considering all the factors characterizing the polymeric material. Such a prediction of the service characteristics of the gear meshing machine can be effectively made using the author's calculation method [23-27].

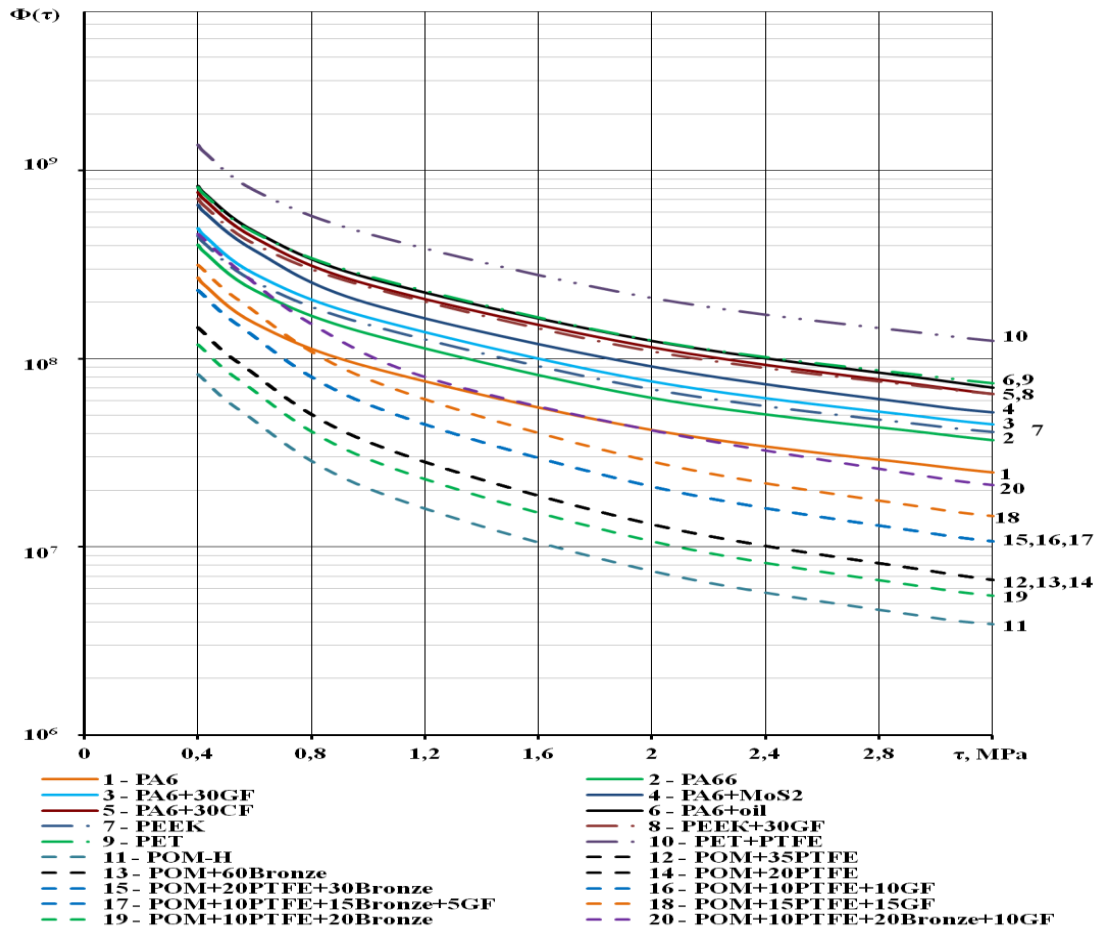


Fig. 7. Diagrams of wear resistance of polymeric materials

For example, the comparative (relative) wear resistance  $\tilde{\Phi}$  of the studied polymeric materials at a specific friction force  $\tau = 2$  MPa is shown in Fig. 8.

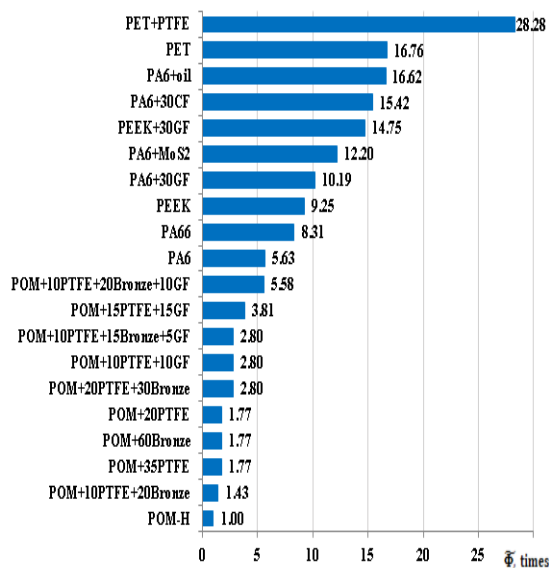


Fig. 8. Relative wear resistance of the investigated polymeric materials

From the analysis of Fig. 7, it is evident that the qualitative nature of the change in the wear resistance functions of different polymeric materials is almost the same, so their relative wear resistance  $\tilde{\Phi}$  at  $\tau = 3$  MPa will be approximately the same (Fig. 8).

The obtained gradation of wear resistance for the main groups of polymeric materials used in mechanical gears indicates the important role of their modification (filling, strengthening), which can lead to a significant improvement in their tribotechnical characteristics.

An important characteristic of the sliding triboprocess is the sliding friction coefficient  $f_i$ . Its experimental values  $f_i$  in tribopairs of polymeric materials - steel 45 at discrete values of the nominal contact pressure  $p_i$  are given in Tables 4-6. Based on these data, the specific friction forces  $\tau_i = f_i p_i$  in the friction contact were calculated.

**Table 4.** Experimental values of sliding friction coefficient for polyamides

No	Polyamides	$p$ , MPa			
		2	4	6	8
1	PA66	0.68±0.1	0.47±0.06	0.355±0.05	0.295±0.025
2	PA6	0.67±0.11	0.45±0.065	0.36±0.06	0.285±0.025
3	PA6+30GF	0.86±0.1	0.72±0.07	0.605±0.045	0.52±0.03
4	PA6+30CF	0.775±0.1	0.615±0.06	0.51±0.06	0.435±0.045
5	PA6+MoS <sub>2</sub>	0.60±0.06	0.37±0.04	0.30±0.03	0.265±0.025
6	PA6+oil	0.71±0.11	0.49±0.05	0.34±0.04	0.31±0.02

**Table 5.** Experimental values of sliding friction coefficient for polyetheretherketones and polyethylene terephthalates

No	Polyetheretherketones Polyethylene terephthalates	$p$ , MPa			
		2	4	6	8
7	PEEK	0.80±0.08	0.61±0.05	0.50±0.04	0.43±0.03
8	PEEK+30GF	0.79±0.09	0.64±0.08	0.53±0.04	0.465±0.015
9	PET	0.64±0.1	0.45±0.05	0.33±0.03	0.27±0.03
10	PET+PTFE	0.6±0.11	0.45±0.05	0.35±0.03	0.295±0.025

**Table 6.** Experimental values of sliding friction coefficient for polyacetals

No	Polyacetals	$p$ , MPa			
		2	4	6	8
11	POM-H	0.54±0.08	0.34±0.04	0.25±0.025	0.23±0.023
12	POM+35PTFE	0.46±0.064	0.33 ± 0.035	0.24 ± 0.025	0.20 ± 0.015
13	POM+60Bronze	0.61± 0.10	0.39 ± 0.06	0.31 ± 0.035	0.28 ± 0.025
14	POM+20PTFE	0.45 ± 0.06	0.32 ± 0.035	0.23 ± 0.025	0.20 ± 0.015
15	POM+20PTFE+30Bronze	0.64±0.11	0.45±0.07	0.35±0.04	0.32±0.03
16	POM+10PTFE+10GF	0.58±0.085	0.37±0.055	0.28±0.040	0.25±0.025
17	ROM+10PTFE+15Bronze+5GF	0.61±0.09	0.41±0.06	0.30±0.045	0.27±0.03
18	POM+15PTFE+15GF	0.56±0.08	0.36±0.045	0.25± 0.03	0.22±0.02
19	POM+10PTFE+20Bronze	0.55±0.07	0.38±0.045	0.26±0.035	0.22±0.02
20	POM+10PTFE+20Bronze+10GF	0.59±0.075	0.39±0.05	0.29±0.035	0.25±0.025

In general, a well-known qualitative pattern of decreasing friction coefficient with increasing contact pressure is observed. It is the lowest in polyacetals over the entire range of contact pressures, slightly higher in polyethylene terephthalates, and approximately the same in some polyamides. The highest values were observed for polyetheretherketones and some polyamide PA6 composites (PA6+30GF, PA6+30CF). The quantitative decrease in the average coefficient of friction when the contact pressure was reduced by a factor of four was in the range of 1.8-2.7 times. In each group of polymers, it was somewhat differentiated. In particular, in polyetheretherketones - by 1.8-1.9 times, in polyethylene terephthalates - by 2.0-2.4 times, in polyacetals - by 2.0-2.5 times, in polyamides - by 2.05-2.7 times.

According to the molecular-mechanical theory of sliding friction of rough bodies, the total coefficient of friction is the sum of the adhesive

(molecular) and deformation (mechanical) components. At low contact pressures, the mechanical component of friction will be dominant with deformation of micro-roughness. Increasing pressures will increase the adhesive component and decrease the deformational component.

An example of the application of the above experimental research results for the assessment of the maximum contact pressures  $p_{jmax}$ , linear wear  $h_{2j}$  of the wheel teeth, and minimum durability  $t_{Bmin}$  of the MP gears using the author's method [26, 27] is given below.

Data for the calculation:

*Materials:* pinion 1 - normalized steel S45,  $E_1 = 210000$  MPa,  $\nu_1 = 0.3$ ,  $\tau_{S1} = 365$  MPa; gear wheel 2 – polyetheretherketones or polyethylene terephthalates (Table 3);

*Parameters:* nominal torque  $T_{nom} = 4000$  Nmm; the number of revolutions of the drive shaft  $n_1 = 700$  rpm; gearing module  $m = 4$  mm; gear ratio  $u = 3$ ; number of wheel teeth  $z_1 = 20$ ,  $z_2 = 60$ ; gear

width  $b = 50$  mm, dynamic coefficient  $K_g = 1.2$ , and permissible wear of the wheel teeth  $h_{2*} = 0.5$  mm.

The results of calculating the maximum contact pressures  $p_{jmax}$  during the engagement cycle are shown in Fig. 9. On the left is the first phase of two-pair meshing, in the center is the phase of single-pair meshing, and on the right - the second phase of two-pair meshing.

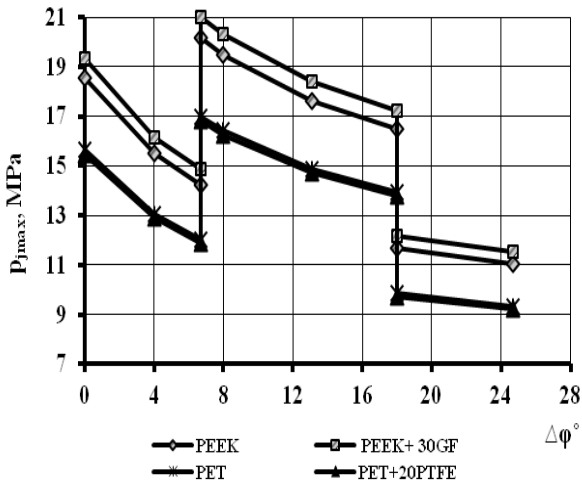


Fig. 9. Maximum contact pressures during the gearing cycle

The results indicate a significant difference in  $p_{jmax}$  during the gearing cycle.

Fig. 10 shows the wear of the wheel teeth up to the permissible value of  $h_{2*} = 0.5$  mm. It will be practically the same at two points - at their entrance to the first phase of the two-pair meshing and at the entrance to the single-pair meshing.

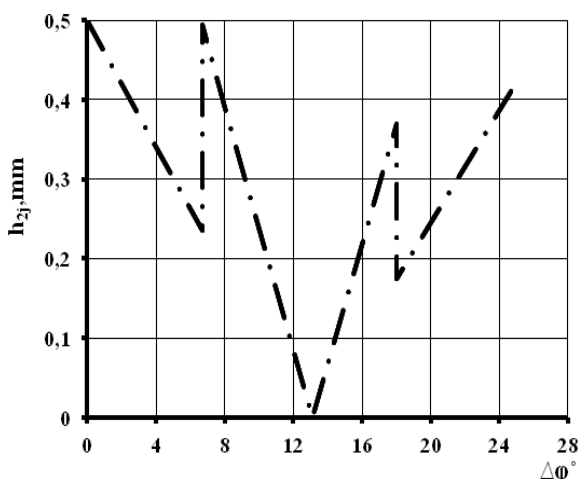


Fig. 10. Linear wear of the polymer wheel tooth profile

The durability  $t_{Bmin}$  of MP gears with a wheel made of the specified types of tribopolymer materials was calculated. The minimum durability  $t_{Bmin}$  will be at the point of engagement, where the

permissible linear wear  $h_{2*} = 0.5$  mm for the polymer wheel teeth is achieved. Accordingly, it will be as follows: PET+20PTFE - 46770 hours, PET - 27760 hours, PEEK+30GF - 18720 hours, PEEK - 12810 hours.

The durability of gearing is determined by the influence of maximum contact pressures, wear resistance of polymers, their elastic modulus and to some extent the Poisson's ratio and friction coefficient.

#### 4. CONCLUSION

The study of polymeric materials of various types for gearing by using a tribometer under normalized and stable environmental conditions has been carried out. The goal to establish indicators and characteristics of wear resistance of a number of polymeric materials for tribological applications has been fully achieved. The qualitative and quantitative regularities of the influence of fillers on the wear resistance of common engineering and high-performance polymeric materials for gearing, namely polyamides, polyacetals, polyetheretherketones, and polyethylene terephthalates, were established. The quantitative characterization of the wear resistance of individual polymeric materials is shown in the diagrams of wear resistance and relative wear resistance. The most wear-resistant polymer PET+PTFE exceeds the wear resistance of the least wear-resistant unfilled polyacetal in POM-H by more than 28 times. In the polymer groups, the wear resistance of their composites significantly depends on the type of fillers. Accordingly, in the groups of polyamides - by 3 times, polyacetals - by 5.6 times, polyetheretherketones - by 1.6 times, and polyetheretherketones - by 1.7 times. A significant difference in the wear resistance was revealed in unfilled polymeric materials at  $\tau = 2$  MPa relative to that of POM-H: PA6 / PA66 / PEEK / PET - by 5.63 / 8.31 / 9.25 / 16.76 times. It is shown that the qualitative patterns of change in their wear resistance when changing the specific friction forces at the tribocontact are similar, as reflected in the summary diagrams of wear resistance (Fig. 7).

Quantitative and qualitative regularities of the change in the friction coefficient in metal-polymer pairs under dry friction from contact pressure were established. In each group of polymers, its quantitative values were differentiated depending on the type of filler. No clear pattern of the

influence of the types of fillers on the friction coefficient has been established. It was shown that the filling of the basic polymer with glass fiber causes its increase in PA6+30GF and PEEK+30GF. The type of basic polymer also affected the value of the friction coefficient.

The research results, presented in the form of a summary diagram of wear resistance, will be of great practical importance in engineering practice when optimizing the choice of gear material in terms of wear resistance. The results of the above studies were partially used to calculate metal-polymer gears for tooth contact pressures, wear, and durability in the works of the authors [26, 27]. They can be used for similar studies of MP gears of various types, the gear wheel of which is made of the studied types of polymeric materials, for tribotechnical purposes. Also, using dependences (3), it is possible to recalculate the wear resistance indicators  $\Phi$  of polymers into the intensity  $I_h$  of linear wear and Archard's wear coefficient  $K_w$  and vice versa. Accordingly, this ensures the use of the presented research results in the tribology of polymeric materials and engineering practice in the design of MP gears.

#### CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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