TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special II, April, 2024

DETERMINATION OF THE TRIBOTECHNICAL CHARACTERISTICS OF THE MATERIALS USED FOR PRECESSIONAL TRANSMISSIONS DESIGN

Gheorghe POȘTARU, Petru STOICEV, Andrei POȘTARU, Ion BODNARIUC, Alexandru BUGA, Andrei PLATON

Abstract: *An extensive study was made on the tribological behavior of the contact of the precessional transmission (PT) gear. The research was carried out on tribomodels at an SMT-1 type installation according to a methodology previously developed by the authors. The concave-convex contact of teeths of the PT was simulated in the non-conformist research by contact between two cylindrical rollers with different diameters. The cylindrical rollers were made from the materials taken in the study. In the framework of the experimental research, based on a study carried out by the authors, were used metallic and plastic materials, recommended for the design and manufacture of gear wheels. Obtained research results, allowed the choice of the materials for the gear wheels manufacturing for PT and the lubrication type from the point of view of the tribological behavior of the contact (according to the anti-friction criterion).*

Key words: *precessional transmission (PT), tribomodels, lubrication, metallic and plastic materials, summary friction coefficient (f_Σ), normal loading force (F_N), friction force (F_{fr}).*

1. INTRODUCTION

The present paper is a continuation of the research carried out by the authors [1, 2, 3, 4] with the aim of determining the tribological behavior of the materials used in the design and manufacturing of the low-power precessional transmission gears. As part of the research carried out, were selected different combinations of plastic and metallic materials couples (metal-metal, metal-plastic, plastic-plastic). Following of materials recommendations in [2 - 4], was studied on the tribological models the behavior of the materials in the following combinations: steel 40Cr-steel 40Cr; steel 40Cr - POM; POM-POM. The couple of the tribological models (fig.2) were run on special testing machine SMT 1 in operating conditions without lubrication and with lubrication (MULTIS EP 2 grease). During non-conformist researches was highlighted steel 40Cr-POM couple materials, from the point of view of the lower heat in contact zone and the low friction coefficient.

In this paper also was studied, the tribological behavior of other materials recommended in [3], under lubrication conditions with solid greases and liquid lubricants.

2. MATERIALS AND RESEARCH METHODS

In the practical researches was used following materials: steel 40 Cr (GOST4543-2016) and plastic materials POM and PEEK [6] from CEPROINV Company [5]. Lubricants were used to lubricate the contract: MULTIS EP 2 grease [7]; oil for mechanical transmissions (TRANS GEAR SAE 75W90 API GL 5 [8]).

In the fig.1a is presented the PT, for which the research in question is intended. The PT consist from two central wheel (fixed wheel Z_1 and movable wheel Z_4), and satellite with Z_2 and Z_3 teeth [4].

The tests were performed on tribomodels at the SMT-1 type installation (model 2070) belonging to the Tribology laboratory of the

Technical University of Moldova (UTM). In modeling was imposed the condition of a geometric and kinematic similarity between the convex-concave contact Z_1/Z_2 and Z_3/Z_4 of the PT and the convex-convex contact of the model made with cylindrical rollers used in the SMT-1 type installation (fig. 1b-c) [4].

As a rule, when designing the low-power PT the plastic materials are recommended for the satellite and for movable and fixed wheels – plastic or steel [3]. For this reason, the pair of materials was combined in following variants (fig.2): Z1-PEEK/Z2-PEEK and Z1- steel 40Cr/ Z2-PEEK; Z3-PEEK/ Z4-PEEK; Z3-PEEK/ Z4-steel 40Cr.

The research was carried out based on the methodology [3] specially developed for the study of the tribological behavior of the contact for PT gear and carried out experimentally in [4], using machines and devices for the acquisition and computerized processing of experimental data.

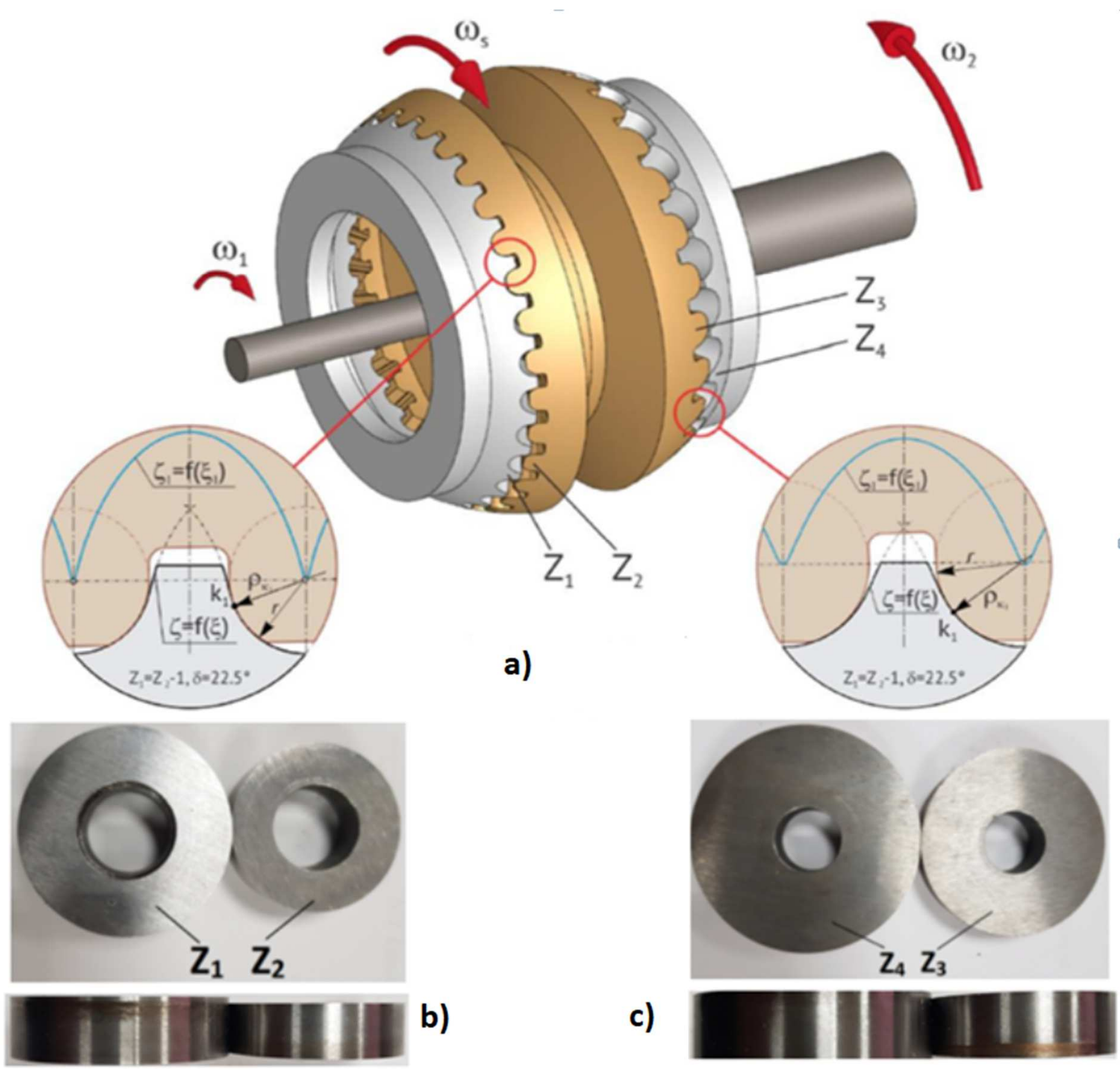
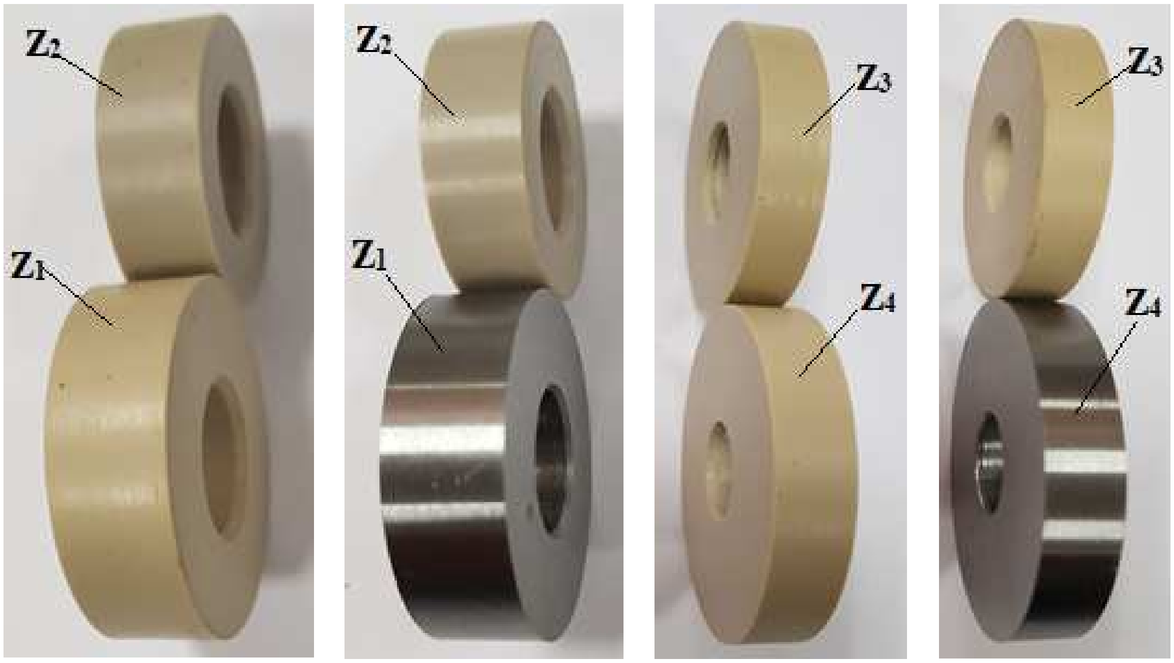


Fig.1. The general view representation of the PT $A^{D(\beta)}_{CX-CV}$ and the shape of the flank profile of the teeth (a); the tribomodel contact Z_1/Z_2 (b); the tribomodel contact Z_3/Z_4 (c)



a) b) c) d)

Fig.2. The combination of the tribological couples subjected to experimental tests: a) - Z_1/Z_2 (PEEK/PEEK); b) - Z_1/Z_2 (40Cr/ -PEEK); c) - Z_3 /Z_4 (PEEK/ PEEK); d - Z_3 /Z_4 (PEEK/ - 40Cr)

Respecting the conditions of geometric and kinematic similarity in the contact area between teeth (Z_1/Z_2, Z_3 /Z_4) (fig.1a) were calculated and manufactured rolls with the diameters: Z_1 – d = 38,42 mm; Z_2 – d = 31,75 mm; Z_3 – d =48,81 mm; Z_4 – d = 56,29 mm. The length of the contact line is b = 11 mm.

3. THE RESULTS OF SCIENTIFIC RESEARCH

Chemical composition and characteristics of the materials subjected to the experimental tests:

- Steel 40Cr **[5]** (Fe, %-97; C-0,36…0,44; Si, %-0,17…0,37; Ni, % - 0,3; Mn,% - 0,5…0,6; Cr,% - 0,8…1,1; oil quenching (T=860°C) tempering (500-800°C). tensile strength R_B-665 MPa; Yield point, σ_{02}- 490 MPa; Hardness HB – 212…248; Elongation after break δ, % - 15; impact absorbing energy, I/cm^2-59).
- Polyetheretherketone (PEEK) **[6]**: Specific Gravity - 1,3g/cm^3; Molding Shrinkage – 1,0-%......1,60%; Impact Strength (section - notched / unnotched: 91 J/m; 747 J/m; Tensile Strength –265 MPa; Tensile Elongation -1,4 %; Tensile Modulus - 34475 MPa ; Flexural Strength – 379 MPa; Melt Temperature -349...399°C; Drying-149°C; Dew Point: -29°C; price: PEEK – 280 $/kg, price: POM - 28 $/kg.

The loading of the contract was carried out in stages, with its maintenance over time until the stabilization of the temperature (T) in the friction zone. The load level was limited at the time of the appearance of the qualitative change in the evolution of the tribological parameters and the working surfaces.

For the comparative analysis of the tribological behavior of the rollers, the experimental tests were carried out in the presence or absence of the contact lubrication medium. The temporal evolution of the tribological characteristics in the case of testing Z_1/Z_2 model (PEEK/PEEK) in operating conditions without lubrication is shown in fig.3. The results of the statistical processing of the data obtained experimentally, according to temporal evolution, are presented in table 1 and fig.4.

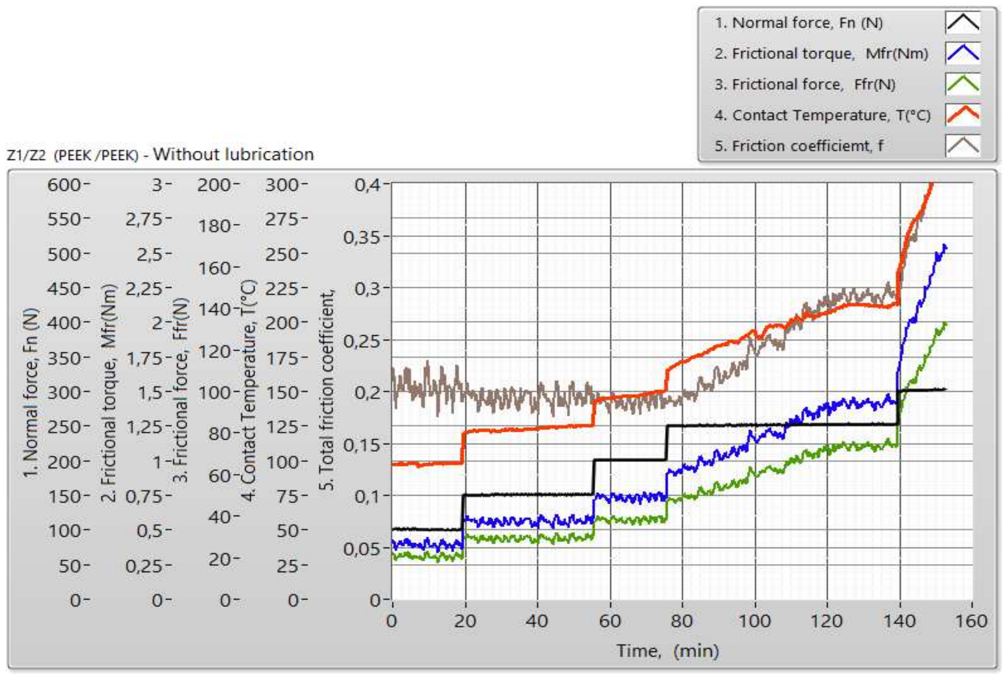


Fig.3. Temporal evolution of the tribological parameters (F_n, M_{fr}, F_{fr}, T, f) by loading the contact in steps with the normal force, ($\Delta F_n = 50N$). Z_1/Z_2 model (PEEK/PEEK). Without lubrication

Table 1

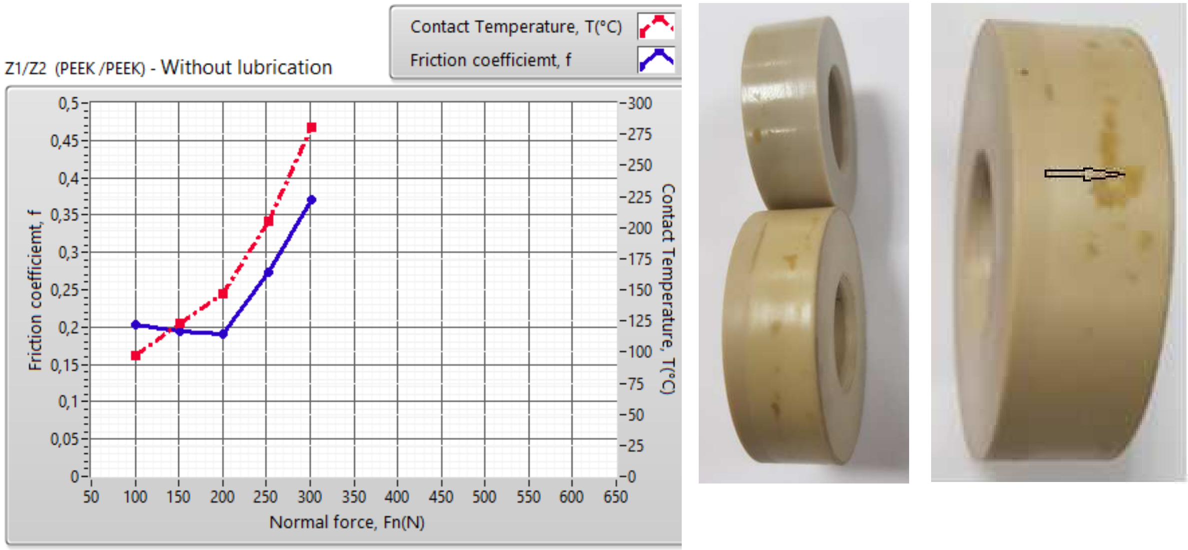
The values of the tribological parameters obtained as a result of the statistical processing of the experimental data. Z_1/Z_2 (PEEK/PEEK) – Without lubrication

Fn (N)	Mfr, (Nm)	St. Dev. Mfr	Ffr, (N)	St. Dev. Ffr	T (°C)	St. Dev. T	f	St. Dev. f	RMS f	Pdis. (W
100,583	0,394	0,021	20,507	1,110	97,611	0,484	0,204	0,011	0,204	3,402
150,830	0,562	0,021	29,276	1,115	123,020	1,422	0,194	0,007	0,194	4,859
201,088	0,736	0,021	38,311	1,075	146,689	1,866	0,191	0,005	0,191	6,359
252,025	1,328	0,094	69,123	4,909	204,774	7,071	0,274	0,019	0,275	11,429
301,791	2,147	0,223	111,766	11,618	280,836	20,427	0,370	0,038	0,372	18,536

The experimental data demonstrated a different tribological behavior of the contact during loaded with the normal force Fn. Within normal force variation limits up to 200 N, the friction coefficient has stable values within the limits of 0,19...0,2, and the temperature in the contact area ranging from 97°C to 145°C (fig.4a). The high level of temperature is explained by the reduced transfer of heat from the contact area to the surrounding environment, due very low heat transfer coefficient of the PEEK.

When the contact is loaded with the force $F_n > 200N$ (fig. 3, fig. 4a), an intensive increase in the friction coefficient and temperature occurs, which probably leads to structural changes in the surface layers of the materials in the friction areas. Structural changes are also demonstrated by the appearance on the friction surfaces of areas in the form of dark spots of different sizes, randomly distributed (fig. 4b-c).

Upon reaching a value of 300 N of the normal force F_n, the friction coefficient and correspondingly the temperature in the contact area increase suddenly (the temperature exceeding the values of 295°C and approaching the level of the melting temperature 349°C...399°C for PEEK). This behavior indicates that the limit level of contact bearing capacity for the PEEK/PEEK material pair has been reached. Taking into account the obtained results, it can be concluded that the use of the PEEK/PEEK material pair can only be possible for loads with reduced normal force $F_n \approx 200...250$ N.



a) **b)** **c)**

Fig.4. Variation of the friction coefficient *(f)* and contact temperature ***(T)*** for the Z_1/Z_2 couple (PEEK/PEEK - rolls). Without lubrication

Of particular interest represented the tribological behavior of the contact of the PT gear when operating under lubrication conditions. In accordance with the recommendations made, lubrication was carried out with MULTIS EP2 grease [7] and with transmission oil TRANS GEAR SAE 75W90 [8].

The test results demonstrated a particularly high efficiency of the lubricants on the tribological behavior of the contact for both models of couplings (Z_1/Z_2, Z_3/Z_4) and of the pairs of the materials (PEEK/PEEK, 40Cr/ PEEK, PEEK/ 40Cr), both according to the anti-friction criterion (the friction coefficient ***f***) and the level of temperature ***(T)*** developed in contact.

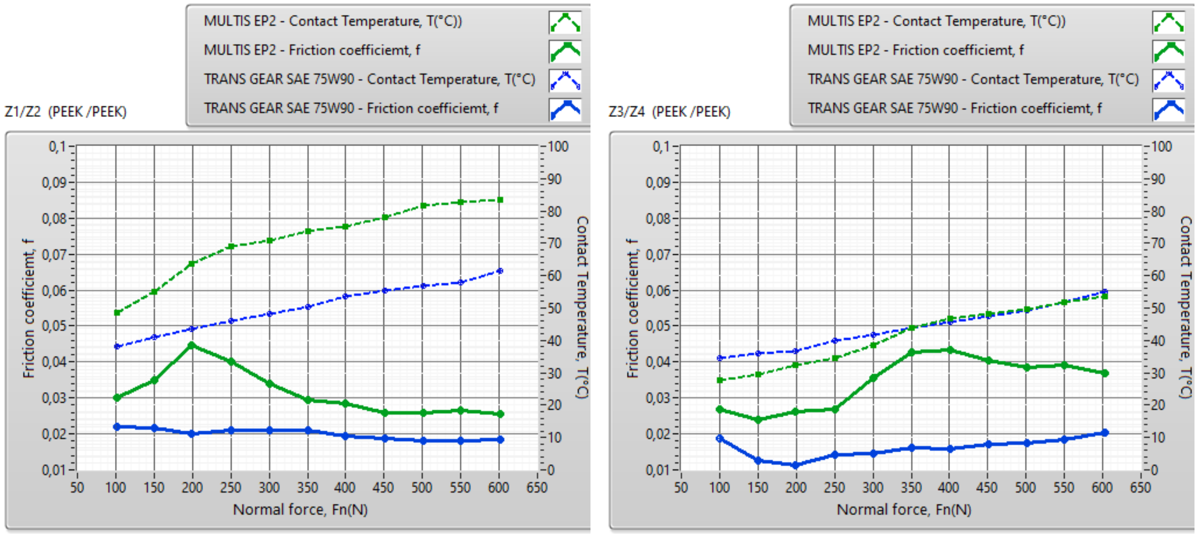
A variant of the results of the statistical processing of the experimental data is presented in table 2.

The figures 5 and 6 show the experimental data obtained as a result of statistical processing according to the temporal evolution of the tribological behavior of the contact of the tribomodels Z_1/Z_2 and Z_3/Z_4, lubricated by MULTIS EP2 grease, and with transmission oil TRANS GEAR SAE 75W90.

Table 2

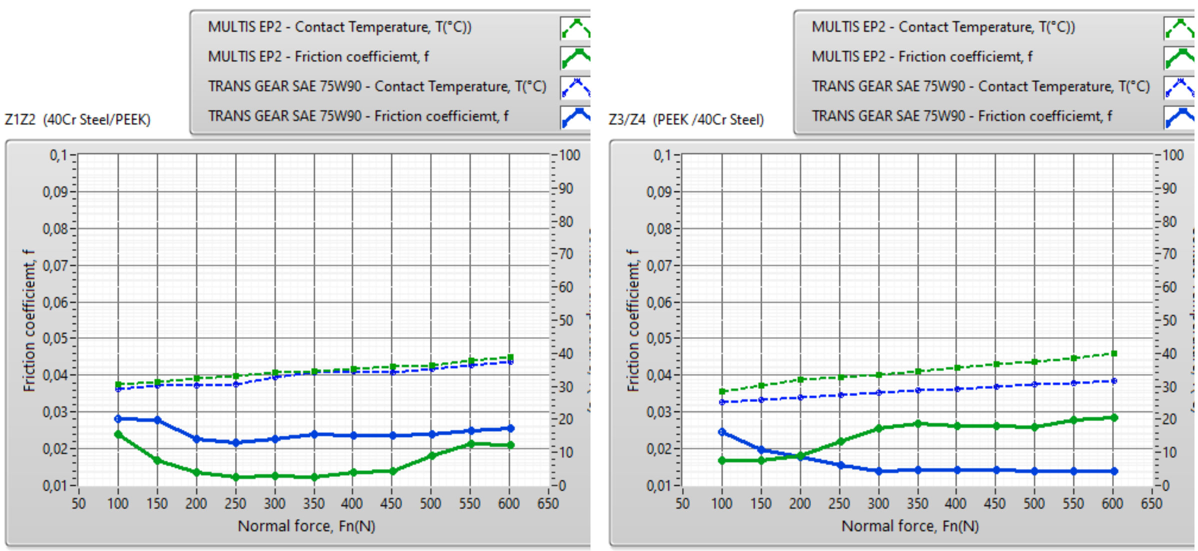
The values of the tribological parameters obtained as a result of the statistical processing of the experimental data. Z_1/Z_2 (PEEK/PEEK) – lubrication TRANS GEAR SAE 75W90.

Fn (N)	Mfr, (Nm)	St. Dev. Mfr	Ffr, (N)	St. Dev. Ffr	T (°C)	St. Dev. T	f	St. Dev. f	RMS f	Pdis. (W
100,154	0,042	0,018	2,208	0,943	44,470	0,118	0,022	0,009	0,024	0,367
149,741	0,062	0,018	3,224	0,917	46,906	0,426	0,022	0,006	0,022	0,535
200,322	0,077	0,017	3,996	0,909	49,170	0,365	0,020	0,005	0,020	0,663
250,822	0,101	0,018	5,266	0,959	51,284	0,430	0,021	0,004	0,021	0,875
301,328	0,122	0,018	6,356	0,923	53,349	0,293	0,021	0,003	0,021	1,053
350,728	0,142	0,020	7,374	1,034	55,343	0,265	0,021	0,003	0,021	1,222
401,074	0,150	0,019	7,789	0,987	58,356	0,921	0,019	0,002	0,020	1,291
450,204	0,161	0,018	8,374	0,945	59,788	0,248	0,019	0,002	0,019	1,388
500,768	0,175	0,018	9,126	0,961	61,219	0,240	0,018	0,002	0,018	1,514
550,352	0,190	0,020	9,896	1,048	62,157	0,244	0,018	0,002	0,018	1,642
601,304	0,215	0,020	11,169	1,016	65,214	1,286	0,019	0,002	0,019	1,854



a) **b)**

Fig.5. Variation of the friction coefficient (***f***) and temperature (***T***) when loading the contact with the normal force (F_n) for material pairs: a –Z_1/Z_2 (materials– PEEK/PEEK); b - Z_3/Z_4 (materials – PEEK/PEEK). Lubrication: (MULTIS EP 2- grease); transmission oil (TRANS GEAR SAE 75W90)



a) **b)**

Fig.6. Variation of the friction coefficient (***f***) and temperature (***T***) when loading the contact with the normal force (F_n) for material pairs: a – Z_1/Z_2 (materials - 40Cr/ PEEK); b - Z_3/Z_4 (materials – PEEK/ 40Cr). Lubrication: (MULTIS EP 2- grease); transmission oil (TRANS GEAR SAE 75W90)

The PEEK/PEEK pair lubricated with MULTIS EP 2 grease the friction coefficient ***f*** vary between 0,025...0,04, and temperature in area of contact was between 40°C...80°C (fig.5a-b). Was observed a positive influence of the lubricant that made possible to widen the load range of the contact with the normal force F_n up to 600N, without qualitative changes in the tribological evolution. But in the case when was used transmission oil TRANS GEAR SAE 75W90 as lubricated solution, for Z1/Z2 model, the friction coefficient ***f*** was 0.02.

For the Z_3/Z_4 model (fig.5b) was observed increase of the friction coefficient from 0,012 till 0,02 at loading normal force Fn = 600N. The temperatures in the area of contact for both models varied between 40°C...60°C. The decrease in temperature is a consequence of the low level of energy dissipation in the contact area (power dissipation P_{dis} = 0,5...2,5 W).

A similar tribological behavior was also confirmed by the tests performed with the pairs of following materials: **40Cr/PEEK** - for Z_1/Z_2 model and PEEK**/ 40Cr** - for Z_3/Z_4 model (fig. 6a-b). In both lubricated cases (MULTIS EP 2 or TRANS GEAR SAE 75W90) – the friction coefficient remains low from 0,012 till 0,028 over the entire load range on the contact (Fn = 100...600N). Also, due to low level of dissipation energy (power dissipation P_{dis} = 0,3...3,3 W) and the heat transfer conditions in the contact area (when a roll is metallic), the stabilization temperature remains at low level (35°C...45°C).

4. CONCLUSIONS

As a result of the experimental work, was established:

For the PEEK/PEEK unlubricated pair rolls, was observed contradictory tribological behavior with possible structural changes of the material in the friction areas. For this reason, it is recommended to avoid use PEEK without lubrication in PT.

For the PEEK/PEEK, 40Cr/PEEK, PEEK/ 40Cr, rolls pair, operating with lubrication (MULTIS EP 2 grease or RANS GEAR SAE 75W90 transmission oil) the friction coefficient is particularly low and does not exceed the value of 0.04.

During operating with lubrication (MULTIS EP 2 grease or RANS GEAR SAE 75W90 transmission oil) the PEEK/ 40Cr, rolls pair, showed good tribological behavior.

Research has shown that PEEK has more superior mechanic performances than polyamides (POM) and polyacetals (PA).

PEEK can be used at high contact loadings, high temperature, and high torques. Only then the high price of this material can be economically justified.

Acknowledgements: The article was published by the authors by conducting scientific research under the State Research-Innovation Project, No. 160-PS of 31.01.2020 "Increasing the competitiveness of precessional transmissions by developing and capitalizing on the gear with conform contact of the teeth and expanding their application area”. Project number 20.80009.700.24, dated 31.01.2020. Project leader - Acad. Ion Bostan.

5. REFERENCES

[1] Bostan. I. *Preţessionâe peredaci s mnogoparnâm zaţepleniem.* Izd. „Ştiinţa”, 341 s., ISSN/ISBN, Chişinău, 1991.

[2] Bostan, I., Stoicev, P., Buga, A.., Poștaru, Gh., Trifan, N., Platon. A. *Theoretical contributions on the selection of possible tribological couples of materials for the manufacture of precessional transmissions,* Journal of Engineering Science, Publishing House ,,Tehnica-UTM”, Vol. XXIX, no. 1 (2022), pp. 23 – 47, ISSN 2587-3474, eISSN 2587-3482.

[3] Bostan, I., Stoicev, P., Poștaru, Gh., Vaculenco, M., Buga, A., Culev, A., Poștaru, M., Platon. A. *Theoretical and experimental modelling of the tribological behaviour aspects of contact elements in the precessional gearing.* Journal of Engineering Science, Publishing House ,,Tehnica-UTM”, Vol. XXIX, no. 2 (2022), pp. 8 - 17. ISSN 2587-3474, eISSN 2587-3482.

[4] Bostan, I., Stoicev, P., Poștaru, Gh., Buga, A., Bodnariuc, I., Poștaru, A., Platon. A. *Particularities of tribological behavior of the contact elements of the precessional gear, made of metallic and plastic materials.* ModTech 2023, International Conference - Modern Technologies in Industrial Engineering, June 14-17, 2023, Bucharest, Romania, International Journal of Modern Manufacturing Technologies, Special Issue: New Frontiers in Industrial Engineering, XV(3)/2023 (in editing, abstract ID A-9), https://modtech.ro/conference/book-of-abstracts.php#gsc.tab=0

[5] *Stal` 40x- GOST4543-2016*, http://www.atissteel.ru/stal-40h-harakteristiki

[6] *Mase plastice POM, PEEK*, (Exporter: SC CEPROIN .V S.A., str. Luceafărului no.16, cart. Madrestt – cdd620043, Focșani -

Romania WATT number RO1440484), http://www.isar.com.ro

[7] *Grease MULTIS EP.2,* https://total-er.com/sites/g/files/wompnd1106/f/atoms/files/multis_ep_2.pdf

[8] *Ulei pentru transmisii mecanice TRANS GEAR SAE 75W90 API GL5*, https://www.penrite.info/en/manual-transmission-differential-gear-oils/trans-gear-75w-90

Determinarea caracteristicilor tribotehnice ale materialelor utilizate pentru proiectarea transmisiilor precesionale

Cercetările au fost efectuate pe tribomodele, la o instalație de tip SMT-1 conform unei metodologii elaborate anterior de autori. Tribomodelul cu forma contactului „convex-convexă" (format din două role cilindrice cu diametre diferite), prevăzut pentru instalația dată, a fost echivalat cu contactul de formă „concav-convexă" al dinților conjugați din angrenajul transmisiei precesionale (TP) reale, din punct de vedere geometric și cinematic. Rolele - model au fost executate din materialele luate în studiu. În cadrul cercetărilor experimentale, în baza unui studiu realizat de către autori, s-au aplicat materiale metalice și plastice, recomandate pentru proiectarea și fabricarea roților dințate. Rezultatele cercetărilor obținute, pentru cazuri concrete de funcționare, au permis alegerea materialelor roților angrenajelor TP și a mediului de lubrifiere din punct de vedere a comportamentului tribologic a contactului (conform criteriului de antifricțiune).

Cuvinte cheie: *Transmisie Precesională (TP), tribomodel, lubrifiere, materiale metalice și plastice, coeficient de frecare sumar (f_{Σ}), forță normală de încărcare (F_N), forță de frecare (F_{fr}).*

Gheorghe POȘTARU, PhD Associate Prof., Technical University of Moldova, Faculty of Mechanical Engineering, Studentilor str., Nr.9/8, Chisinau city, Republic of Moldova, post code MD-2020, gheorghe.postaru@bpm.utm.md

Petru STOICEV, Prof.Univ.Emer., PhD.Hab., Technical University of Moldova, Faculty of Mechanical Engineering, Studentilor str., Nr.9/8, Chisinau city, Republic of Moldova, post code MD-2020, petru.stoicev@imi.utm.md

Andrei POSTARU, PhD Student, Technical University of Moldova, Faculty of Mechanical Engineering, Studentilor str., Nr.9/8, Chisinau city, Republic of Moldova, post code MD-2020, andrei.postaru@ati.utm.md

Ion BODNARIUC, PhD Associate Prof., Technical University of Moldova, Faculty of Mechanical Engineering, Studentilor str., Nr.9/8, Chisinau city, Republic of Moldova, post code MD-2020, ion.bodnariuc@bpm.utm.md

Alexandru BUGA, PhD Lecturer, Technical University of Moldova, Faculty of Mechanical Engineering, Studentilor str., Nr.9/8, Chisinau city, Republic of Moldova, post code MD-2020, alexandru.buga@precesia.utm.md

Andrei PLATON, PhD Student, Technical University of Moldova, Faculty of Mechanical Engineering, Studentilor str., Nr.9/8, Chisinau city, Republic of Moldova, post code MD-2020, andrei.platon@bpm.utm.md