DEVELOPMENTS IN MECHANICAL ENGINEERING
ISSN: 2300-3383 DOI: 10.37660/dme.2020.15.8.6 **15(8)2020**

Finding the correlation between wear of samples kinematic pair of conformal contact and electric power consumption

Jarosław Robert Mikołajczyk[1]

[1] Stanisław Staszic University of Applied Sciences in Piła; e-mail: jmikolajczyk@puss.pila.pl

Summary: The article presents a statistical analysis of the mass variation of samples of kinematic pair of conformal contact and variation of electric power consumption of tribotester. The analysis of dependence between the mass of samples Δm and power variation ΔP for tested consumable and relative motion velocity were carried out with the help of correlation methods using R software [1, 2, 3].

Key words: surface texture, surface layer, base oil, oil additives, consumable, statistic

1. Introduction

The friction is characterized by the loss of mechanical energy. This energy undergoes a transformation or it is dissipated. Processes of energy loss at friction may be divided into the following phases:

- performance of work in the contact area (forming a real contact surface);
- energy conversion into work of elastic, plastic deformation and adhesion;
- energy dissipation (conversion into heat, emission, cumulation).

The result of above mentioned energy conversions are, inter alia, wear processes. However, that which is called a wear is the process of variations in the surface layer of a solid body characterized by a mass decrement or permanent surface deformation. The result of a wear process is a wear measured by weight, linearity or volume. This paper presents a dependence between the size of mass decrement Δm [mg] of tested samples on the volume of electric power consumption P [kW] of a tribotester for tested consumables and examined relative motion velocities of kinematic pair of conformal contact. The analysis was performed on the basis of R software.

2. Test conditions

Values, which constitute the set of input factors, were selected on the basis of gathered literature information and preliminary tests:

- average relative motion velocity v;
- type of lubricating compound.

The average velocity of relative motion during the test amounted to: 0.16 m/sec and 0.08 m/sec.

Samples with a counter sample were mating at the external load of 600 N which – for the contact surface of samples with a counter sample amounting to 300 mm^2 – corresponds to the theoretical pressure in the contact zone of 2.0 MPa.

Taking into account the material of samples and counter sample, the following hardness of samples was adopted: 40 HRC, and for a counter sample: 60 HRC.
As additives to SN-150 oil base selected were consumables: Motor Life and Mind M. For their selection i followed the criteria listed below: availability, operations mechanism, purpose. Apart from that no research was found in the analyzed literature as regards testing of a lubricating compound of consumables mentioned above. The first mentioned consumable is widespread in Poland. It caused the modification of the surface layer by creating a boundary layer as a result of physisorption and chemisorption. It contain synthetic base component, anti-wear additives, antioxidants, extreme pressure additives. Where as Mind M constitutes a hydrocarbon complex which combines chemically with the metal of the base forming a microscopic monomolecular layer which cannot be washed out. It distributes pressure forces on a greater surface thereby increasing of construction materials. It interacts with the metallic base (ferrous or non-ferrous) mainly in places of an increased temperature of the friction process.

Producers of consumables mentioned above recommend their 5% concentration in the oil base. In order to learn more about their operation, both lower than this value and higher concentration values were used in this paper. The following concentrations were used: 0% (pure oil base); 0.5%; 1%; 2%; 5% and 7% of tested additive in the oil base. The third consumable was a composition consisting of Motor Life and Mind M in a 1:1 ratio of concentrations mentioned above.

On the basis of literature information, for the set of output factors taken were values which characterize the wear process, including the mass decrement Δm whose statistical analysis prepared in R software is presented below.

Mass decrement is an absolute measure of wear commonly used in the research and industrial practice. It is a value which describes the wear process in a representative way.

Constant factors in the tests included the construction material of samples, i.e. steel 102Cr6 (NC6). This steel is characterized by, inter alia, a small hardness straggling after heat treatment, therefore in order that hardness of samples is within a narrow range, this material was selected for testing. Samples were in the shape of a cube measuring 10 × 10 × 10 [mm].

It was assumed that the material of a counter sample and its hardness (H) remained unchanged during the tests. Thus, these features of samples were also included into the constant factors. A counter sample was made of steel X210Cr12 (formerly NC11) quenched to the hardness of 60±2 HRC. The hardness of the counter sample was much greater than the hardness of samples in order that the process of wear be directed, and results of transformation of the surface layer be visible primarily on samples. The condition of the surface texture of the counter sample was periodically controlled – its texture did not show any significant symptoms of wear.

Conditions of treatment of tested elements were also accepted as constant factors – ground surface, friction face equal to L = 2000 [m], pressure force of the counter sample onto samples F = 600 [N], work temperature (temperature in which the transformation of the surface layer took place) equal to the ambient temperature: +20°C.

Random, uncontrolled input factors – disturbances include inter alia:

- vibrations resulting from deviations of structure elements of the test rig;
- contamination of the work environment;
- diversification of geometric surface of samples caused for example by the process of wear of tools during the treatment;
- variation of the pressure force resulting from the installation deviation of the spring deflection as well as progressive wear of samples;
- samples hardness straggling caused for example by heterogeneity of the samples material in its whole volume.

Tested samples were fixed in three grooves every 120° on the face of the bush stabilizing samples in order to ensure a reliable and uniform three-surface pressure of mating elements.

For the relative motion velocity v_2 = 0.16 m/sec, the path of friction L = 2000 m was reached after 200 minutes. The measurement of power input was carried out every one second. Thus, 200 × 60 = 12000 measurements were made for each concentration of a tested consumable.

For the relative motion velocity v_1 = 0.08 m/sec, the path of friction L = 2000 m reached after 400 minutes. The measurement of power input was carried out every one second. Thus, 400 × 60 = 24000 measurements were made for each concentration of a tested consumable [4].

2. Tests results

For measured values of power consumption ΔP and mass decrement of samples Δm calculated were, using R software, the following statistical parameters in order to analyze the obtained results:

- Min – minimum value;
- 1tQu. – lower (first) sample quartile (Q_1);
- Median – median ('medial value' Q_2);
- Mean – arithmetic mean;
- 3rdQu. – upper (third) sample quartile (Q_3);
- Max – maximum value;
- IQR – interquartile range;
- R – sample range;
- s – standard deviation;
- d_1 – average deviation from the mean value.

Statistical parameters mentioned above are tabulated in Table 1, Table 2, Table 4 and Table 5 (for Composition); in Table 7, Table 8, Table 10 and Table 11 (for Motor Life); in Table 13, Table 14, Table 16 and Table 17 (for Mind M).

Table 1. List of selected statistical parameters for measured power consumptions [kW] for the Composition consumable. Relative motion velocity v_1 = 0.08 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.0	1.6	1.9	2.3	3.1	0.7	3.1	0.436	0.367	1.984
0.5%	0.0	1.6	1.9	2.4	3.3	0.8	3.3	0.499	0.423	1.994
2%	0.0	1.6	1.8	2.1	2.9	0.5	2.9	0.375	0.375	1.879
5%	0.0	1.7	1.9	2.3	3.0	0.6	3.0	0.406	0.338	1.979
7%	0.0	1.7	2.0	2.3	3.2	0.6	3.2	0.413	0.336	2.006

Table 2. List of selected statistical parameters for measured mass [mg] decrements of samples for the Composition consumable. Relative motion velocity v_1 = 0.08 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.1	0.1	0.3	0.5	0.7	0.4	0.6	0.229	0.192	0.3333
0.5%	0.0	0.1	0.2	0.4	0.7	0.3	0.7	0.218	0.172	0.2556
1%	0.1	0.1	0.2	0.3	0.6	0.2	0.5	0.181	0.140	0.2556
2%	0.0	0.1	0.2	0.2	0.4	0.1	0.4	0.123	0.093	0.1556
5%	0.0	0.1	0.1	0.2	0.4	0.1	0.4	0.123	0.096	0.1556
7%	0.0	0.0	0.1	0.3	0.4	0.3	0.4	0.150	0.128	0.1556

In order to determine a possible dependence between ΔP and Δm correlations were calculated using the Pearson's and Spearman's method. It was assumed at the same time that results have a normal distribution. If correlation values are close to 1 or -1 value, then variables are dependent. If correlation values are close 0 value, then we deal with independent variables. Results are presented in Table 3, Table 6, Table 9, Table 12, Table 15 and Table 18.

Table 3. Results of correlation between individual power inputs of the tribological system and the wear of samples of kinematic pair of conformal contact for defined concentrations of Composition consumable. Relative motion velocity v_1 = 0.08 m/sec, path of friction L = 2000 m

PE Composition [%]	Measured mass decrement Δm [mg]	Measured power consumption ΔP [kW]	Pearson	Spearman
0	0.3333	1.984		
0.5	0.2556	1.994		
2	0.1556	1.879	0.3230403	0.2236068
5	0.1556	1.979		
7	0.1556	2.006		

Table 4. List of selected statistical parameters for measured power consumptions [kW] for the Composition consumable. Relative motion velocity v_2 = 0.16 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.0	3.2	3.5	4.0	4.9	0.8	4.9	0.486	0.412	3.577
0.5%	0.0	3.3	3.5	4.0	4.9	0.7	4.9	0.434	0.367	3.621
2%	0.0	2.8	3.1	3.6	4.6	0.8	4.6	0.478	0.408	3.187
5%	0.0	2.8	3.0	3.5	4.3	0.7	4.3	0.444	0.383	3.146
7%	0.0	3.2	3.5	4.0	4.9	0.8	4.9	0.469	0.404	3.500

Table 5. List of selected statistical parameters for measured mass [mg] decrements of samples for the Composition consumable. Relative motion velocity v_2 = 0.16 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.1	0.1	0.2	0.3	0.5	0.2	0.4	0.15	0.125	0.233
0.5%	0.0	0.1	0.2	0.3	0.6	0.2	0.6	0.18	0.133	0.233
1%	0.1	0.1	0.3	0.3	0.5	0.2	0.4	0.14	0.118	0.233
2%	0.1	0.1	0.1	0.2	0.3	0.1	0.2	0.07	0.061	0.155
5%	0.0	0.0	0.1	0.1	0.3	0.1	0.3	0.09	0.059	0.088
7%	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.05	0.044	0.033

Table 6. Results of correlation between individual power inputs of the tribological system and the wear of samples of kinematic pair of conformal contact for defined concentrations of Composition consumable. Relative motion velocity v_2 = 0.16 m/sec, path of friction L = 2000 m

PE Composition [%]	Measured mass decrement Δm [mg]	Measured power consumption ΔP [kW]	Pearson	Spearman
0	0.233	3.577		
0.5	0.233	3.621		
2	0.155	3.187	0.4558334	0.6668859
5	0.088	3.146		
7	0.033	3.500		

Table 7. List of selected statistical parameters for measured power consumptions [kW] for the Motor Life consumable. Relative motion velocity v_1 = 0.08 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.0	1.6	1.9	2.3	3.1	0.7	3.1	0.436	0.367	1.984
0.5%	0.0	1.6	1.9	2.3	3.1	0.7	3.1	0.422	0.356	1.936
1%	0.0	1.6	1.8	2.2	3.0	0.6	3.0	0.403	0.337	1.895
2%	0.0	1.6	1.9	2.3	3.0	0.7	3.0	0.444	0.378	1.935
5%	0.0	1.5	1.7	2.1	2.9	0.6	2.9	0.424	0.359	1.823
7%	0.0	1.7	1.9	2.2	3.0	0.5	3.0	0.388	0.323	1.943

Table 8. List of selected statistical parameters for measured mass [mg] decrements of samples for Motor Life. Relative motion velocity v_1 = 0.08 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.1	0.1	0.3	0.5	0.7	0.4	0.6	0.229	0.192	0.3333
0.5%	0.0	0.2	0.3	0.4	0.5	0.2	0.5	0.156	0.118	0.2778
1%	0.0	0.1	0.3	0.4	0.8	0.3	0.8	0.243	0.180	0.2778
2%	0.0	0.2	0.2	0.3	0.9	0.1	0.9	0.264	0.177	0.3000
5%	0.0	0.0	0.1	0.2	0.3	0.2	0.3	0.120	0.096	0.1222
7%	0.0	0.1	0.1	0.1	0.3	0.0	0.3	0.092	0.061	0.1111

Table 9. Results of correlation between individual power inputs of the tribological system and the wear of samples of kinematic pair of conformal contact for defined concentrations of Motor Life consumable. Relative motion velocity v_1 = 0.08 m/sec, path of friction L = 2000 m

PE Motor Life [%]	Measured mass decrement Δm [mg]	Measured power consumption ΔP [kW]	Pearson	Spearman
0	0.3333	1.984		
0.5	0.2778	1.936		
1	0.2778	1.895	0.5701984	0.3188741
2	0.3000	1.935		
5	0.1222	1.823		
7	0.1111	1.943		

Table 10. List of selected statistical parameters for measured power consumptions [kW] for the Motor Life consumable. Relative motion velocity v_2 = 0.16 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.0	3.2	3.5	4.0	4.9	0.8	4.9	0.486	0.412	3.577
0.5%	0.0	3.2	3.4	3.8	4.8	0.6	4.8	0.425	0.355	3.498
1%	0.0	3.0	3.3	3.8	4.7	0.8	4.7	0.461	0.391	3.413
2%	0.0	2.9	3.2	3.7	4.6	0.8	4.6	0.490	0.424	3.281
5%	0.0	2.8	3.1	3.6	4.6	0.8	4.6	0.513	0.443	3.205
7%	0.0	3.0	3.3	3.7	4.8	0.7	4.8	0.471	0.402	3.369

Table 11. List of selected statistical parameters for measured mass [mg] decrements of samples for Motor Life. Relative motion velocity v_2 = 0.16 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.1	0.1	0.2	0.3	0.5	0.2	0.4	0.15	0.125	0.233
0.5%	0.0	0.0	0.1	0.1	0.3	0.1	0.3	0.10	0.066	0.100
1%	0.0	0.1	0.2	0.4	0.4	0.3	0.4	0.16	0.125	0.211
2%	0.0	0.0	0.2	0.3	0.4	0.3	0.4	0.16	0.148	0.166
5%	0.0	0.0	0.1	0.2	0.4	0.2	0.4	0.13	0.113	0.122
7%	0.0	0.0	0.1	0.1	0.2	0.1	0.2	0.07	0.059	0.088

Table 12. Results of correlation between individual power inputs of the tribological system and the wear of samples of kinematic pair of conformal contact for defined concentrations of Motor Life consumable. Relative motion velocity v_2 = 0.16 m/sec, path of friction L = 2000 m

PE Motor Life [%]	Measured mass decrement Δm [mg]	Measured power consumption ΔP [kW]	Pearson	Spearman
0	0.233	3.577	0.396517	0.3714286
0.5	0.100	3.498		
1	0.211	3.413		
2	0.166	3.281		
5	0.122	3.205		
7	0.088	3.369		

Table 13. List of selected statistical parameters for measured power consumptions [kW] for the Mind M consumable. Relative motion velocity v_1 = 0.08 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.0	1.6	1.9	2.3	3.1	0.7	3.1	0.436	0.367	1.984
0.5%	0.0	1.6	1.8	2.1	2.9	0.5	2.9	0.381	0.316	1.872
1%	0.0	1.6	1.8	2.1	2.9	0.5	2.9	0.344	0.280	1.874
2%	0.0	1.7	1.8	2.0	2.7	0.3	2.7	0.270	0.215	1.842
5%	0.0	1.6	1.9	2.2	3.1	0.6	3.1	0.435	0.356	1.900
7%	0.0	1.5	1.7	2.1	3.0	0.6	3.0	0.416	0.353	1.830

Table 14. List of selected statistical parameters for measured mass [mg] decrements of samples for Mind M. Relative motion velocity v_1 = 0.08 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.1	0.1	0.3	0.5	0.7	0.4	0.6	0.229	0.192	0.3333
0.5%	0.0	0.1	0.2	0.2	0.3	0.1	0.3	0.101	0.081	0.1556
1%	0.0	0.1	0.1	0.2	0.4	0.1	0.4	0.123	0.096	0.1556
2%	0.0	0.0	0.0	0.1	0.3	0.1	0.3	0.111	0.088	0.0666
5%	0.0	0.0	0.0	0.1	0.3	0.1	0.3	0.109	0.086	0.0777
7%	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.033	0.019	0.0111

Table 15. Results of correlation between individual power inputs of the tribological system and the wear of samples of kinematic pair of conformal contact for defined concentrations of Mind M consumable. Relative motion velocity v_1 = 0.08 m/sec, path of friction L = 2000 m

PE Motor Life [%]	Measured mass decrement Δm [mg]	Measured power consumption ΔP [kW]	Pearson	Spearman
0	0.3333	1.984	0.9027469	0.8116794
0.5	0.1556	1.872		
1	0.1556	1.874		
2	0.0666	1.842		
5	0.0777	1.900		
7	0.0111	1.830		

Table 16. List of selected statistical parameters for measured power consumptions [kW] for the Mind M consumable. Relative motion velocity v_2 = 0.16 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.0	3.2	3.5	4.0	4.9	0.8	4.9	0.486	0.412	3.577
0.5%	0.0	2.9	3.2	3.7	4.6	0.8	4.6	0.523	0.443	3.298
1%	0.0	3.1	3.5	3.9	4.8	0.8	4.8	0.479	0.401	3.527
2%	0.0	3.0	3.2	3.6	4.3	0.6	4.3	0.355	0.300	3.320
5%	0.0	3.0	3.3	3.9	4.8	0.9	4.8	0.498	0.429	3.453
7%	0.0	2.9	3.2	3.6	4.5	0.7	4.5	0.419	0.356	3.260

Table 17. List of selected statistical parameters for measured mass [mg] decrements of samples for Mind M. Relative motion velocity v_2 = 0.16 m/sec, path of friction L = 2000 m

	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d_1	Mean
0%	0.1	0.1	0.2	0.3	0.5	0.2	0.4	0.15	0.125	0.233
0.5%	0.0	0.0	0.1	0.2	0.3	0.2	0.3	0.11	0.088	0.100
1%	0.0	0.1	0.2	0.2	0.3	0.1	0.3	0.10	0.081	0.155
2%	0.0	0.0	0.2	0.3	0.4	0.3	0.4	0.15	0.125	0.166
5%	0.0	0.0	0.0	0.1	0.2	0.1	0.2	0.07	0.061	0.055
7%	0.0	0.0	0.0	0.1	0.3	0.1	0.3	0.10	0.074	0.066

Table 18. Results of correlation between individual power inputs of the tribological system and the wear of samples of kinematic pair of conformal contact for defined concentrations of Mind M consumable. Relative motion velocity v_2 = 0.16 m/sec, path of friction L = 2000 m

PE Motor Life [%]	Measured mass decrement Δm [mg]	Measured power consumption ΔP [kW]	Pearson	Spearman
0	0.233	3.577	0.5945848	0.5428571
0.5	0.100	3.298		
1	0.155	3.527		
2	0.166	3.320		
5	0.055	3.453		
7	0.066	3.260		

3. Summary

From the analyzed consumables the greatest correlation (both for velocity v_1 and v_2) between ΔP and Δm has Mind M consumable. This proves, inter alia, that for changed values of relative motion velocity (from v_1 to v_2) proportions of variations of power consumption by a tribologic system are proportional to the mass variation of samples (mass decrement) in a degree even functional (for v_1). This is a positive characteristic as it allows to forecast above mentioned parameters when one of them is known.

Practically, for all analyzed consumables, the coefficients of correlation between the electric power consumption and mass variation of samples are average, high or very high. This shows that all correlations are statistically significant. However, for different pairs (P, m) the values of coefficients are different.

At work variations of the mass value in the function of power consumption is treated as a stochastic process, and the mass variation for a given type of consumable and given velocity of a relative motion constitutes the realization of that process.

From the energy point of view, friction is a process in which there is a conversion of energy supplied to the system (work of forces, maintaining mating bodies in a set motion) into other forms of energy. What percentage of energy supplied to the system in this kinematic pair is used for forming a new friction face is one of the fundamental questions regarding the description of energy balance for this case. Further analysis is necessary.

Literature

[1] Biecek, P., „Analiza danych z programem R. modele liniowe z efektami stałymi, losowymi i mieszanymi", Wydawnictwo Naukowe PWN, Warszawa 2013.
[2] Biecek, P., „Przewodnik po pakiecie R", Oficyna Wydawnicza GIS, Wrocław 2017.
[3] Crawley, M., "The R Book" Wiley-Blackwell 2012.
[4] Mikołajczyk, J.R., "Influence of consumables on the amount of power consumption of kinematic vapor of conformal contact", *Developments in Mechanical Engineering* 13(7),(2019), Wydawnictwa Uczelniane UTP w Bydgoszczy.