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STATISTICAL ANALYSIS OF THE MASS VARIATION OF SAMPLES AS A RESULT OF THE WEAR PROCESS

Summary: This paper presents a statistical analysis of the variation of the mass of samples caused by the process of wear of kinematic vapor of conformal contact working in the presence of a consumable of a defined content. It contains the presentation of test conditions and design of a test rig. Tribological tests were carried out at a room temperature for one velocity of relative motion. Determined was the impact of the concentration of a selected consumable in SN-150 oil base on the mass decrement of tested samples. The statistical analysis was produced on the basis of R software.

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

1. INTRODUCTION

The object of research in this paper is the process of wear of samples with conformal contact ongoing in the presence of a consumable of a defined content. In order to find out its course, tests were carried out on a tribological wear test rig. The object of the test were samples in the shape of a cube. A counter sample was in the form of a flat ring-shaped plate.

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 $v_{śr}$,
- type of lubricating compound.

The average velocity of relative motion during the test amounted to: 4.8 $m \cdot min^{-1}$ (0.08 $m \cdot s^{-1}$).

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 consisting of

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consumables mentioned above. The first mentioned consumable is widespread in Poland. It causes the modification of the surface layer by creating a boundary layer as a result of physisorption and chemisorption. It contains synthetic base components, anti-wear additives, antioxidants, extreme pressure additives. Whereas 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 the durability of construction materials. It interacts with the metallic base (ferrous or non-ferrous) mainly in places of an increased temperature of the friction process [11, 12].

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 [15, 16, 18, 19].

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 $10 \times 10 \times 10$ [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: 20ºC.

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 structure 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

Tests were carried out on the rig presented in Fig. 1. Tested samples were fixed in three grooves every 120º on the face of the bush stabilizing samples in order to ensure a reliable and uniform three-surface pressure of mating elements.

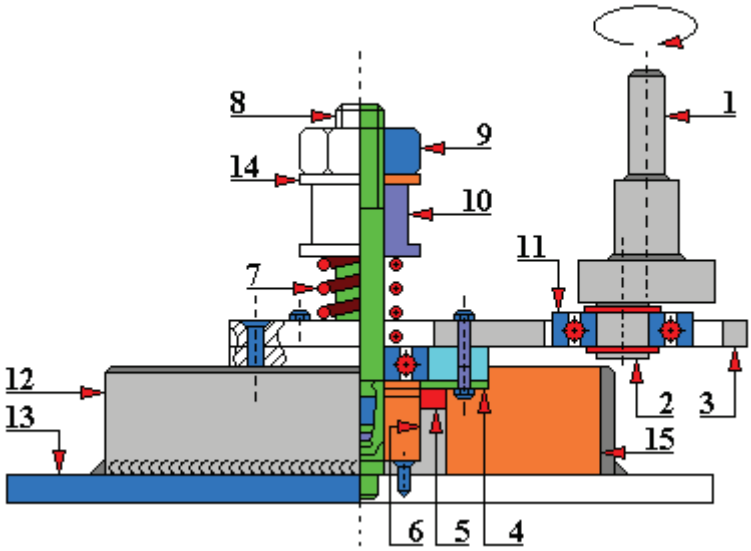

Fig. 1. Structural form of the test rig [15–19]: 1 – eccentric handle, 2 – eccentric, 3 – lever, 4 – counter sample, 5 – tested samples, 6 – samples stabilizing bush, 7 – spring, 8 – central screw, 9 – nut, 10 – distance bush, 11 – single-row ball bearing, 12 – pipe jacket, 13 – steel plate of the base, 14 – washer, 15 – tested lubricating compound

Rys. 1. Postać konstrukcyjna stanowiska badawczego [15–19]: 1 – uchwyt mimośrodu, 2 – mimośród, 3 – dźwignia, 4 – przeciwpróbka, 5 – badane próbki, 6 – tuleja ustalająca próbki, 7 – sprężyna, 8 – śruba centralna, 9 – nakrętka, 10 – tuleja dystansowa, 11 – łożysko kulkowe jednorzędowe, 12 – płaszcz rury, 13 – płyta stalowa podstawy, 14 – podkładka, 15 – badana kompozycja smarowa

3. TEST RESULTS

Table 1 presents measured mass decrements of samples on the length L = 2000 m at a relative motion velocity V = 0.08 $m \cdot s^{-1}$ mating with a counter sample immersed in Composition consumable. 0% indicates pure oil base

SN-150 (100%) without additives. Mass decrement of 0.0 mg indicates that the mass decrement was below the sensitivity threshold of a balance (wear traces testify for it). These data were implemented into R software in order to generate a box plot [1–10, 13, 14, 20, 21].

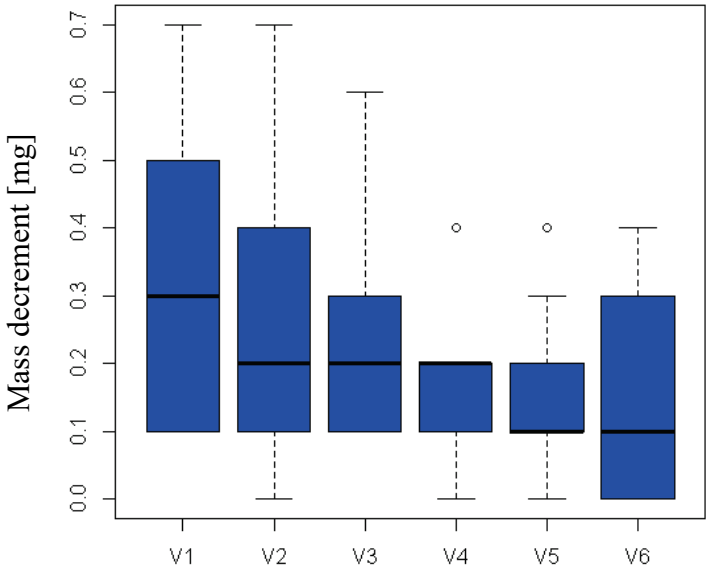

Fig. 2. A box plot generated in R software referring to the samples mass decrement for different concentrations of the Composition consumable. Relative motion velocity V = 0.08 m·s^{-1}, path of friction L = 2000 m; on the vertical axis – mass decrement [mg]; V1 – pure oil base (100% SN-150); V2 – 0.5% Composition consumable, V3 – 1% Composition consumable, V4 – 2% Composition consumable, V5 – 5% Composition consumable, V6 – 7% Composition consumable

Rys. 2. Wykres pudełkowy wygenerowany w programie R dotyczący ubytku masy próbek dla różnych stężeń PE Kompozycja; prędkość ruchu względnego V = 0,08 m·s^{-1}, droga tarcia L = 2000 m; na osi pionowej – ubytek masy [mg]; V1 – czysta baza olejowa (100% SN-150); V2 – 0,5% PE Kompozycja, V3 – 1% PE Kompozycja, V4 – 2% PE Kompozycja, V5 – 5% PE Kompozycja, V6 – 7% PE Kompozycja

Table 1. Mass increment [mg] of samples for particular concentrations of Composition consumable; relative motion velocity V = 0.08 m·s^{-1} [15, 16, 19]

Tabela 1. Ubytki masy [mg] próbek dla poszczególnych stężeń PE Kompozycja; prędkość ruchu względnego V = 0,08 m·s^{-1} [15, 16, 19]

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9
0%	**0.2**	**0.3**	**0.6**	**0.1**	**0.5**	**0.7**	**0.1**	**0.4**	**0.1**
0.5%	**0.3**	**0.1**	**0.4**	**0.7**	**0.0**	**0.2**	**0.4**	**0.1**	**0.1**
1%	**0.2**	**0.2**	**0.5**	**0.6**	**0.1**	**0.1**	**0.3**	**0.2**	**0.1**
2%	**0.1**	**0.2**	**0.2**	**0.2**	**0.0**	**0.2**	**0.4**	**0.1**	**0.0**
5%	**0.1**	**0.3**	**0.1**	**0.1**	**0.1**	**0.1**	**0.4**	**0.2**	**0.0**
7%	**0.4**	**0.3**	**0.0**	**0.0**	**0.1**	**0.1**	**0.0**	**0.3**	**0.2**

In order to analyze the obtained results the following statistical parameters were calculated, using R software, for measured values of the mass decrement of samples:

- Min – minimum value;
- 1stQu. – 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 2.

Table 2. List of selected statistical parameters for measured mass decrements of samples for the Composition consumable

Tabela 2. Zestawienie wybranych parametrów statystycznych dla zmierzonych ubytków masy próbek dla PE Kompozycja

	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 individual mass decrements of samples for given concentrations of tested Composition consumable, 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 to 0 value, then we deal with independent variables. Results are presented in Table 3.

Table 3. Results of correlation between individual concentrations of the Composition consumable. Relative motion velocity V = 0.08 m·s^{-1}, path of friction L = 2000 m

Tabela 3. Wyniki korelacji pomiędzy poszczególnymi stężeniami PE Kompozycja. Prędkość ruchu względnego V = 0,08 m·s^{-1}, droga tarcia L = 2000 m

	Pearson		Spearman	
0%	-0.34		-0.29	
0.5%		0.89		0.82
1.0%	0.45		0.63	
2%		0.75		0.61
5%	-0.05		0.00	
7%				

Next, in Table 4 presented are measured mass decrements of samples for particular concentrations of the next consumable – Motor Life, on the basis of which – after their implementation into R software – a box plot was made (Fig. 3).

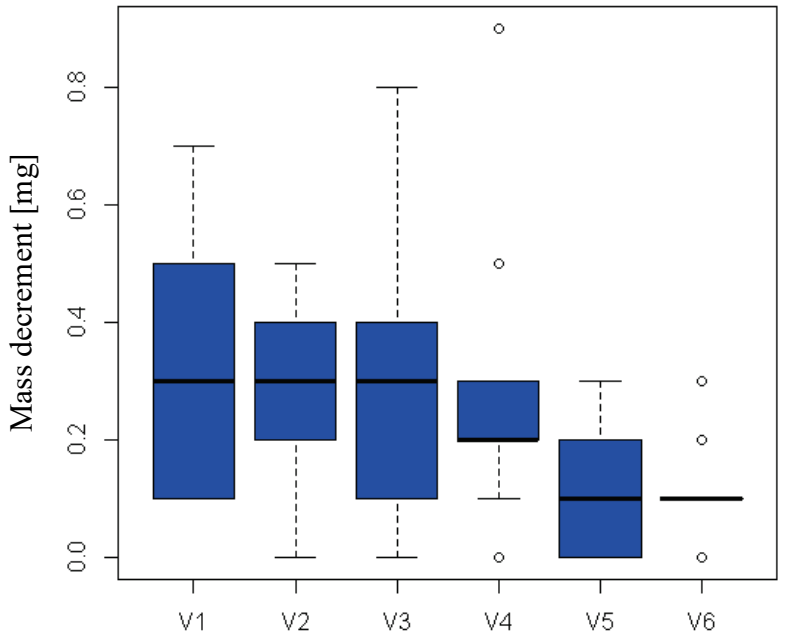

Fig. 3. A box plot generated in R software referring to the mass decrement of samples for different concentrations of Motor Life consumable; relative motion velocity V = 0.08 m·s^{-1}, path of friction L = 2000 m; on the vertical axis – mass decrement [mg]; V1 – pure oil base (100% SN-150); V2 – 0.5% Motor Life consumable, V3 – 1% Motor Life consumable, V4 – 2% Motor Life consumable, V5 – 5% Motor Life consumable, V6 – 7% Motor Life consumable

Rys. 3. Wykres pudełkowy wygenerowany w programie R dotyczący ubytku masy próbek dla różnych stężeń PE Motor Life; prędkość ruchu względnego V = 0,08 m·s^{-1}, droga tarcia L = 2000 m; na osi pionowej – ubytek masy [mg]; V1 – czysta baza olejowa (100% SN-150); V2 – 0,5% PE Motor Life, V3 – 1% PE Motor Life, V4 – 2% PE Motor Life, V5 – 5% PE Motor Life, V6 – 7% PE Motor Life

Table 4. Mass increments [mg] of samples for particular concentrations of Motor Life consumable; relative motion velocity V = 0.08 m·s^{-1}, path of friction L = 2000 m [15, 16, 19]

Tabela 4. Ubytki masy [mg] próbek dla poszczególnych stężeń PE Motor Life; prędkość ruchu względnego V = 0,08 m·s^{-1}, droga tarcia L = 2000 m [15, 16, 19]

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9
0%	**0.2**	**0.3**	**0.6**	**0.1**	**0.5**	**0.7**	**0.1**	**0.4**	**0.1**
0.5%	**0.1**	**0.3**	**0.5**	**0.3**	**0.4**	**0.4**	**0.2**	**0.3**	**0.0**
1%	**0.0**	**0.8**	**0.4**	**0.4**	**0.3**	**0.1**	**0.3**	**0.1**	**0.1**
2%	**0.3**	**0.5**	**0.2**	**0.2**	**0.9**	**0.3**	**0.2**	**0.1**	**0.0**
5%	**0.1**	**0.1**	**0.3**	**0.2**	**0.0**	**0.3**	**0.1**	**0.0**	**0.0**
7%	**0.1**	**0.1**	**0.0**	**0.1**	**0.0**	**0.1**	**0.1**	**0.3**	**0.2**

In order to analyze the obtained results the selected statistical parameters were calculated, using R software, for measured values of the mass decrement of samples: Statistical parameters mentioned above are tabulated in Table 5.

Table 5. List of main statistical parameters of measured mass decrements of samples for Motor Life consumable; relative motion velocity V = 0.08 m·s^{-1}, path of friction L = 2000 m

Tabela 5. Zestawienie głównych parametrów statystycznych zmierzonych ubytków masy próbek dla PE Motor Life; prędkość ruchu względnego V = 0,08 m·s^{-1}, droga tarcia 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

In order to determine a possible dependence between individual mass decrements of samples for given concentrations of tested Motor Life consumable, 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 to 0 value, then we deal with independent variables. Results are presented in table 6.

Table 6. Results of correlation between individual concentrations of Motor Life consumable; relative motion velocity V = 0.08 m·s^{-1}, path of friction L = 2000 m

Tabela 6. Wyniki korelacji pomiędzy poszczególnymi stężeniami PE Motor Life; prędkość ruchu względnego V = 0,08 m·s^{-1}, droga tarcia L = 2000 m

	Pearson		Spearman	
0%	0.79		0.83	
0.5%		0.37		0.44
1.0%	0.34		0.23	
2%		-0.15		0.15
5%	-0.47		-0.43	
7%				

The last consumable, for which tests were conducted, was Mind M, for which in table 7 presented are mass decrements of samples depending on its concentrations in the oil base SN-150. For these data, upon their implementation into R software, generated is the box plot (Fig. 4).

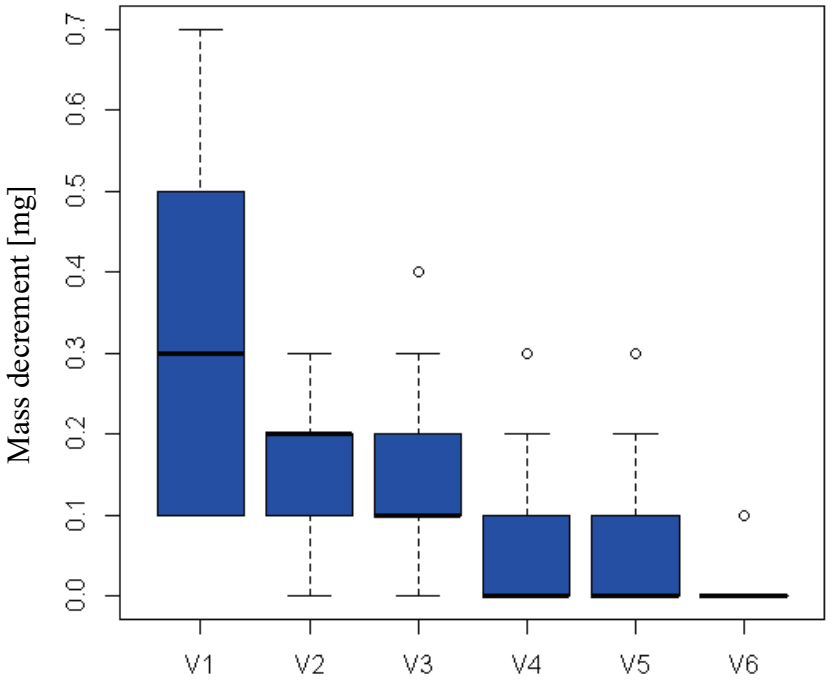

Fig. 4. A box plot generated in R software referring to the mass decrement of samples for different concentrations of Mind M consumable; relative motion velocity V = 0.08 m·s^{-1}, path of friction L = 2000 m; on the vertical axis – mass decrement [mg]; V1 – pure oil base (100% SN-150); V2 – 0.5% Mind M consumable, V3 – 1% Mind M consumable, V4 – 2% Mind M consumable, V5 – 5% Mind M consumable, V6 – 7% Mind M consumable

Rys. 4. Wykres pudełkowy wygenerowany w programie R dotyczący ubytku masy próbek dla różnych stężeń PE Mind M; prędkość ruchu względnego V = 0,08 m·s^{-1}, droga tarcia L = 2000 m; na osi pionowej – ubytek masy [mg]; V1 – czysta baza olejowa (100% SN-150); V2 – 0,5% PE Mind M, V3 – 1% PE Mind M, V4 – 2% PE Mind M, V5 – 5% PE Mind M, V6 – 7% PE Mind M

Table 7. Mass increments [mg] of samples for particular concentrations of Mind M consumable. Relative motion velocity V = 0.08 m·s^{-1}, path of friction L = 2000 m [15, 16, 19]

Tabela 7. Ubytki masy [mg] próbek dla poszczególnych stężeń PE Mind M; prędkość ruchu względnego V = 0,08 m·s^{-1}, droga tarcia L = 2000 m [15, 16, 19]

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9
0%	**0.2**	**0.3**	**0.6**	**0.1**	**0.5**	**0.7**	**0.1**	**0.4**	**0.1**
0.5%	**0.3**	**0.0**	**0.2**	**0.2**	**0.2**	**0.1**	**0.2**	**0.0**	**0.2**
1%	**0.1**	**0.1**	**0.2**	**0.1**	**0.0**	**0.3**	**0.1**	**0.4**	**0.1**
2%	**0.3**	**0.2**	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**	**0.0**	**0.0**
5%	**0.3**	**0.0**	**0.1**	**0.0**	**0.0**	**0.0**	**0.2**	**0.1**	**0.0**
7%	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**

In order to analyze the obtained results the selected statistical parameters were calculated, using R software, for measured values of the mass decrement of samples: Statistical parameters mentioned above are tabulated in Table 8.

Table 8. List of selected statistical parameters of measured mass decrements of samples for Mind M consumable; relative motion velocity V = 0.08 m·s^{-1}, path of friction L = 2000 m

Tabela 8. Zestawienie wybranych parametrów statystycznych zmierzonych ubytków masy próbek dla PE Mind M; prędkość ruchu względnego V = 0,08 m·s^{-1}, droga tarcia 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

4. SUMMARY

The following conclusions can be formulated upon the analysis of obtained characteristics of the mass decrement of tested samples during the process of friction:

- the increase of concentration of the Composition consumable in the oil base SN-150 causes the decrease of average mass decrement of samples from the value of 0.33 mg (pure oil base) to 0.155 mg (for 2%, 5% and 7% Composition consumable) – Fig. 2;
- despite the fact that for Composition consumable concentrations of 0.5% and 1% as well as for 2%, 5% and 7% the mean values of mass decrement are identical, the scatter of results is different – Fig. 2;
- for concentrations of Composition consumable 2% and 5% there are outliers present. It is difficult to determine the cause of their formation, however they do have an impact on the mean value;
- the smallest values of a standard deviation s for Composition consumable appear for concentrations of 2% and 5% (0.123) for which also the average deviation from the mean value d_1 is the lowest (0.096);
- for Composition consumable the concentrations of 0.5% and 1% as well as 2% and 5% are characterized by big values of correlation both in the Pearson's method and Spearman's method (Table 3), i.e. these concentrations are characterized by very similar effects of operation (similar mass decrements of samples);
- the increase of concentration of Motor Life consumable in the oil base SN-150 causes the decrease of average mass decrement of samples from the value of 0.33 mg (pure oil base) to 0.111 mg (7% Motor Life consumable);
- despite the fact that for Motor Life consumable concentrations of 0.5% and 1% identical mean values of the mass decrement were obtained (Fig. 3), the scatter of results is significantly different;
- for Motor Life consumable concentrations of 2% and 7% there are as many as three outliers;
- for Motor Life consumable the smallest standard deviation s is for 7% (0.092) – Table 5;

- for Motor Life consumable only for concentrations of 0% and 0.5% there is a strong correlation of the mass decrement of samples (respectively 0.79 Pearson, 0.83 Spearman); this indicates that small concentrations of this consumable do not have a significant impact on the decrease of the mass decrement of samples;
- for Mind M consumable the increase of concentration in the oil base causes the decrease of average mass decrement of samples from the value of 0.33 mg (pure oil base) to 0.011 mg (for 7%);
- concentrations of Mind M consumable 0.5% and 1% have the same mean value of the mass decrement but different scatter of results (Fig. 4);
- for concentrations of Mind M consumable 1%, 2%, 5% and 7% there are outliers which have an effect on the mean value; it is difficult to determine the cause of such a big number of outlier results for this consumable;
- for Mind M consumable the smallest standard deviation *s* was observed for 7% (0.019).

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ANALIZA STATYSTYCZNA ZMIANY MASY PRÓBEK W WYNIKU PROCESU ZUŻYWANIA

Streszczenie: W pracy przedstawiono analizę statystyczną zmiany masy próbek w wyniku procesu zużywania pary kinematycznej o styku konforemnym, pracującej w obecności preparatu eksploatacyjnego PE o zdefiniowanym składzie. Omówiono warunki badań oraz budowę stanowiska badawczego. Badania tribologiczne wykonano w temperaturze pokojowej dla jednej prędkości ruchu względnego. Określono wpływ stężenia wybranego PE w bazie olejowej SN-150 na ubytek masy badanych próbek. Analizę statystyczną wykonano w oparciu o program R.

Słowa kluczowe: struktura geometryczna powierzchni, warstwa wierzchnia, olej bazowy, dodatki do olejów, preparat eksploatacyjny