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STATISTICAL ANALYSIS OF TRIBOLOGICAL STUDY RESULTS OF THE COEFFICIENT OF FRICTION (DRY AND WET) OF ULTRA-HIGH-MOLECULAR-WEIGHT POLYETHYLENE (UHMWPE), MODIFIED WITH CARBON NANOTUBES (CNTS)

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Abstract: *This article deal with the statistical analysis of the coefficient of friction of new composites based on UHMWPE with the addition of different percentages of carbon nanotubes* (*CNTs*) *- 0.5%, 0.75%, 1.0% and 1.5%. UHMWPE samples with carbon nanotubes, samples of 0.5%, 0.75%, 1.0% and 1.5% carbon nanotubes* (*UHMWPE-CNTs*) *and samples with the same carbon nanotube content were made, but with carbon nanotubes subjected to Electroless Nickel Composite Coating with nanoparticles of SiC* (*UHMWPE-NiCNTs*)*.*
Keywords: *tribology, friction, UHMWPE, carbon nanotubes, composite materials, statistical analysis*

1. INTRODUCTION

The main priority of tribology as interdisciplinary science and technology is to increase the energy efficiency and reliability of machines. It is known that 30% of energy losses in the world are due to friction and 80% of failures in machines belong to friction wear [1÷10]. One of the methods to improve the mechanical and tribological characteristics of UHMWPE is to introduce into the volume of nano-sized particles of different shapes, sizes, concentration and nature [11÷15]. Determination of the kinetic coefficient of friction in sliding is performed with the "thumb-disc" device (Figure 1).

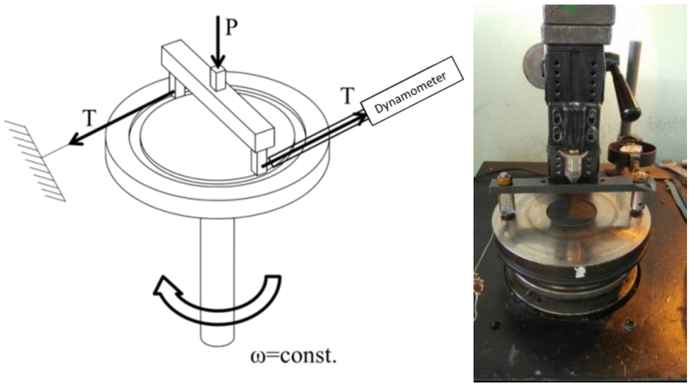

Fig.1. *"Thumb-disk" device for determining the kinetic coefficient of sliding friction*

The thumb is the test specimen and the rotating disc is a high-alloy steel plate of hardness HRC=56,9 and roughness Ra=2.35 μm. The friction force T is measured with a dynamometer attached to the sample holder and located on the tangent of the friction trace in the direction opposite to the movement of the disc. The friction force T is measured with an accuracy of 0.1 N at a set load P and the same friction time

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(friction path). The friction force for all samples is determined by the same friction modes - sliding velocity, load, ambient temperature. The kinetic coefficient of friction is calculated according to the law of Leonardo-Amonton by the formula:

$$\mu = \frac{T}{P} \quad (1)$$

where P is the normal load on the sample. In the present study, experimental results were obtained for the coefficient of friction at four load values for all tested samples under friction conditions without lubricant (dry friction) and for sea water lubrication. With the described methodology and device (Figure 1) the kinetic frictional forces were measured for the tested 10 types of samples at loads P_1=60 N; P_2=80 N; P_3=100N; P_4=120 N, rotation speed n=0.94 min^{-1} and ambient temperature 24°C and the friction coefficients using formula (1) are calculated. The chemical composition of sea water, which is taken from Sozopol, the Black Sea, used in the current experimental work is presented in Table 1.

Table 1.

Chemical composition of the sea water in Black Sea

Chemical element	Weight %
Oxygen (O)	85,80
Hydrogen (H)	10,67
Chlorine (Cl)	2,00
Sodium (Na)	1,07
Magnesium (Mg)	0,14
Calcium (Ca)	0,045
Sulfur (S)	0,039
Potassium (K)	0,038
Bromine (Br)	0,0065
Carbon (C)	0,0035
Strontium (Sr)	0,0010
Boron (B)	0,00045
Fluorine (F)	0,00010
Silicon (Si)	0,00002

The results are presented in Tables 2 (dry) and 3 (wet).

Table 2.

Friction force and coefficient of friction at different normal loads

№	MATERIALS	LOAD, P [N]							
		P_1 = 60		P_2 = 80		P_3 = 100		P_4 = 120	
		T_1, [N]	μ	T_2, [N]	μ	T_3, [N]	μ	T_4, [N]	μ
1	Tufnol	14	0.23	17	0.21	21	0.21	25	0.21
2	UHMWPE-0CNTs	10	0.17	11	0.13	14	0.14	19	0.16
3	UHMWPE-0CNTs*	10	0.17	13	0.16	21	0.21	25	0.21
4	UHMWPE-0.5CNTs	11	0.18	15	0.19	18	0.18	21	0.18
5	UHMWPE-0.75CNTs	14	0.23	15	0.19	17	0.17	20	0.17
6	UHMWPE-1.0CNTs	10	0.17	12	0.15	12	0.12	12	0.10
7	UHMWPE-1.5CNTs	9	0.15	11	0.13	12	0.12	12.5	0.10
8	UHMWPE-0.5Ni-CNTs	12	0.20	14	0.17	17	0.17	19	0.16
9	UHMWPE-1.0Ni-CNTs	23	0.38	26	0.33	25	0.25	27	0.23
10	UHMWPE-1.5Ni-CNTs	14	0.23	18.5	0.23	20	0.20	24	0.20

In Table 3 are presented the results of the friction force and friction coefficient under boundary lubrication with sea water in all samples at a load R=60, 80, 100 and 120 N.

Table 3.

Force and coefficient of friction at boundary lubrication with sea water

№	MATERIALS	LOAD, P [N]							
		P_1 = 60		P_2 = 80		P_3 = 100		P_4 = 120	
		T_1, [N]	μ	T_2, [N]	μ	T_3, [N]	μ	T_4, [N]	μ
1	Tufnol	6	0.10	7	0.09	8	0.08	9	0.08
2	UHMWPE	8	0.13	9	0.11	8	0.08	9	0.08
3	UHMWPE-0 CNTs*	7	0.12	6	0.08	8	0.08	9	0.08
4	UHMWPE-0.5CNTs	8	0.13	9	0.09	11	0.11	13	0.10
5	UHMWPE-0.75CNTs	3	0.05	4	0.05	5	0.05	5	0.04
6	UHMWPE-1.0CNTs	4	0.07	6	0.08	6	0.06	6	0.05
7	UHMWPE-1.5CNTs	5	0.08	7	0.09	6	0.06	7	0.06
8	UHMWPE-0.5Ni-CNTs	8	0.13	8	0.10	7	0.07	9	0.08
9	UHMWPE-1.0Ni-CNTs	8	0.13	9	0.11	9	0.09	8	0.07
10	UHMWPE-1.5Ni-CNTs	7	0.12	5	0.06	5	0.05	8	0.07

2. STATISTICAL ANALYSIS OF THE OBTAINED RESULTS

The following variables are introduced [16÷20]::

Variable	Description	Dimension
Mu	coefficient of friction (COF)	[.]
P	normal load	[N]
TF	friction force	[N]

Material **grouping variable (string)**	**Materials**	***Material_1*** **grouping variable (integer)**
1**D**	Tufnol	1
2**D**	UHMWPE-0CNTs	2
3**D**	UHMWPE-0CNTs*	3
4**D**	UHMWPE-0.5CNTs	4
5**D**	UHMWPE-0.75CNTs	5
6**D**	UHMWPE-1.0CNTs	6
7**D**	UHMWPE-1.5CNTs	7
8**D**	UHMWPE-0.5Ni-CNTs	8
9**D**	UHMWPE-1.0Ni-CNTs	9
10**D**	UHMWPE-1.5Ni-CNTs	10

Each numeric variable is described by a random variable. Each factor being investigated is described by a grouping variable. Each numeric variable is considered separately.

One-way ANOVA: Coefficient of dry friction and analysis of the factor "material"

The factors are studied separately: material (wt% CNTs), normal load. The dependent variable is the coefficient of dry friction. It is necessary to establish that the factors have a response to the dependent variable. According to Table 2, the 40 observations and the 10 levels of the material factor are examined. The mean values with their confidence intervals are shown on Fig.6: number of observations: 40 and number of factor levels: 10

A response is observed with respect to material 9D. In this case, the analysis shows a trend with respect to the other materials. The analysis of the mean values (Figure 3) shows the influence of the factor on the coefficient of friction. Material 9D is distinguished from the rest (Figures 2 and Figure 3).

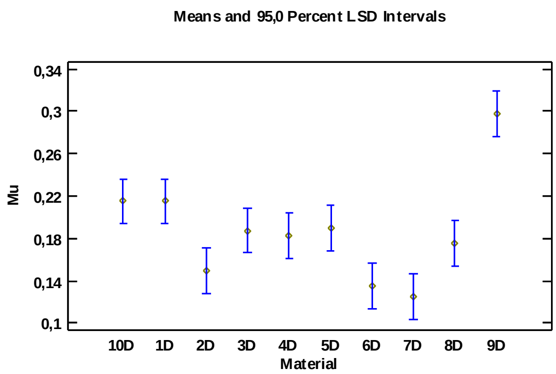

Fig.2. *Mean values and confidence intervals*

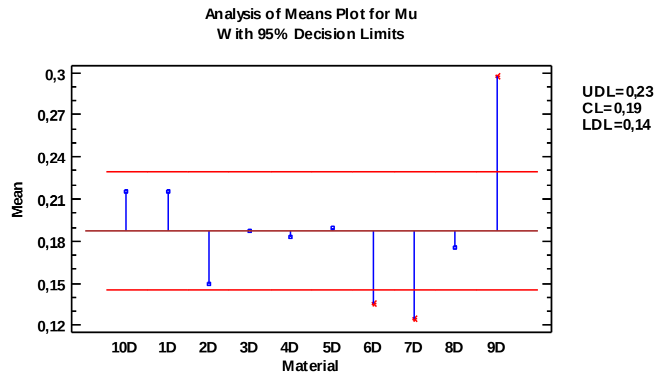

Fig.3. *Investigation of mean values and confidence limits*

If data is censored and material 9D is dropped from the examination, the remaining materials with respect to the coefficient of friction can be represented by the following graph (Figure 4):

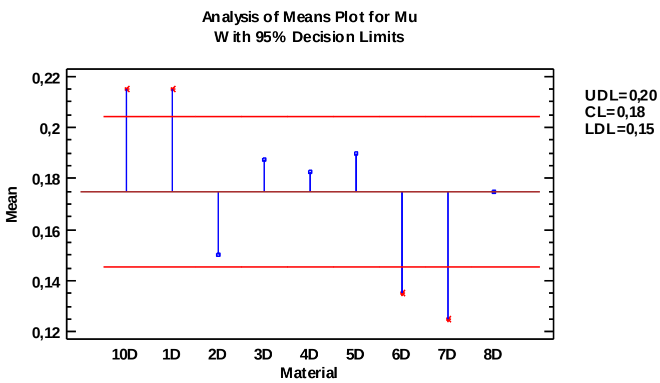

Fig.4. *Mean values of censored data*

Again there is a response to the other materials. In this case, the analysis shows a tendency towards 7B, 8B, as well as materials 10B, 1B.

Multi-factor ANOVA: Friction force when investigating the friction coefficient

The co-influence of factors: "material" and "normal load" on the variable coefficient of friction is examined by a two-factor analysis. In the single factor analysis the influence of the "normal load" factor is not clearly emphasized. The table of average values is illustrated in the following graphs.

With respect to censorship of data, the same reasoning as the previous variable dry friction coefficient (Table 2) can be carried out. The friction force is considered a random magnitude and it is necessary to determine the probability distribution.

One-way ANOVA: Analysis of the factor "material"

The factors are studied separately: material (wt% CNTs) and normal load test. The dependent variable is the friction force. It is necessary to establish that the factors have a response to the dependent variable. According to Table 2, the 40 observations and the 10 levels of the factor “material” are examined. The mean values with their confidence intervals are shown in the following figure (Figure 7). Material 9D differs from the rest.

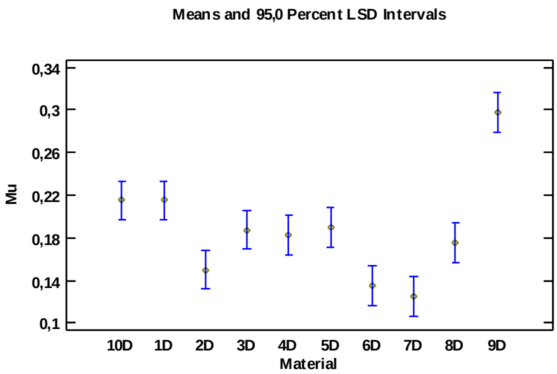

Fig.5. *Mean values with confidence limits*

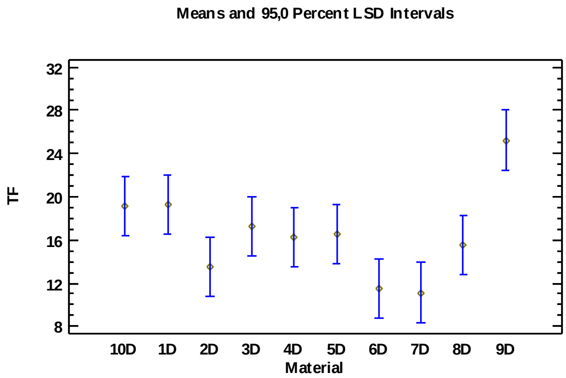

Fig.6. *Investigation of the mean values with confidence limits*

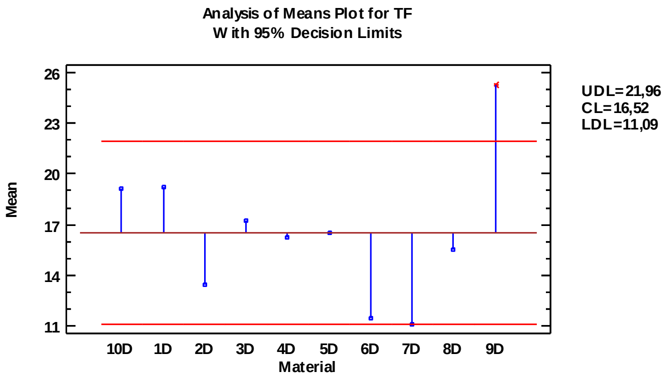

Fig.7. *Analysis of the Mean values*

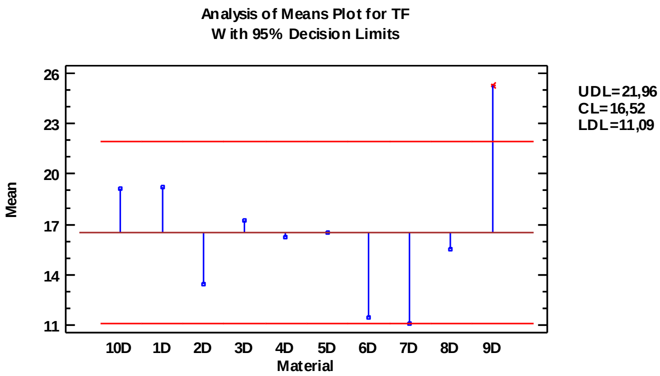

Fig.8. *Mean values for "material" factor and their location versus decision boundaries*

One-way ANOVA: Analysis of the factor "material"

The factors are studied separately: material (wt% CNTs), normal load. The dependent variable is the coefficient of friction at sea water boundary lubrication. It is necessary to establish that the factors have a response to the dependent variable. According to Table 3, the 40 observations and the 10 levels of the material factor were examined. The average values with their confidence intervals are shown in the following figure (Figure 9): number of observations: 40 and number of factor levels: 10

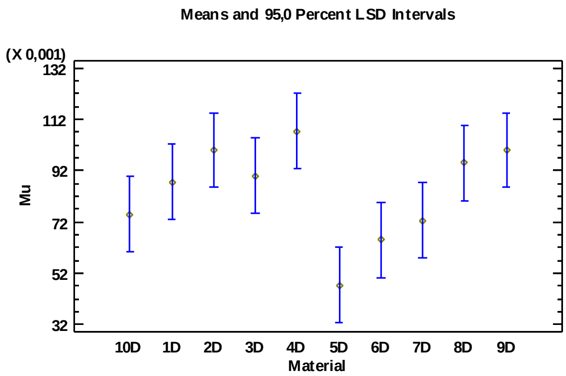

Fig.9. *Mean values and confidence intervals*

A response is observed with respect to material 5D. In this case, the analysis shows two trends with respect to the other materials. The analysis of the mean values (Figure 11) shows the influence of the factor on the coefficient of friction.

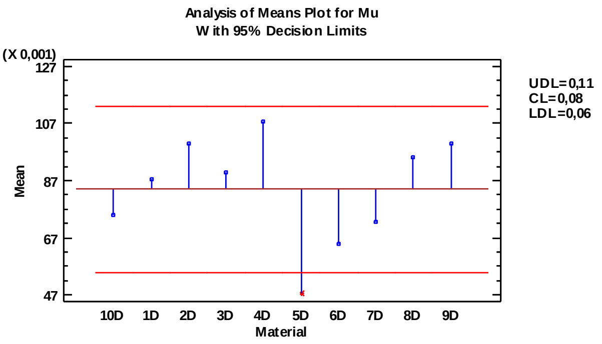

Fig.10. *Investigation of mean values and confidence limits*

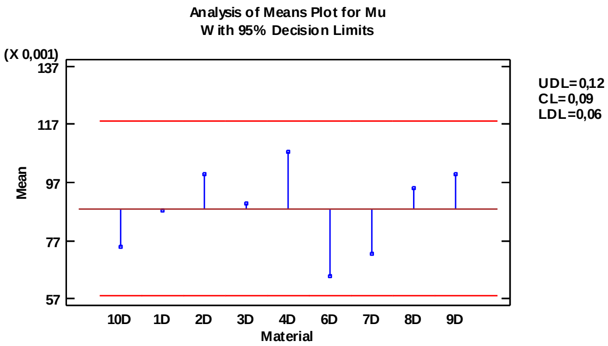

Fig.11. *Mean values of censored data*

Material 5D differs from the rest of Figure 9. If data is censored, material 5D is dropped from the examination, the remaining materials with respect to the coefficient of friction can be represented by the following graph (Figure 11). There is no response to other materials. The trend in the form of two parallel trends is clearly shown in the figure.

Multi-factor ANOVA: Friction force for friction coefficient analysis at sea water boundary lubrication

The joint influence of factors: "material" and "normal load" on the variable coefficient of friction is examined by a two-factor analysis. In the single factor analysis, the impact of the "normal load" factor is not clearly highlighted.

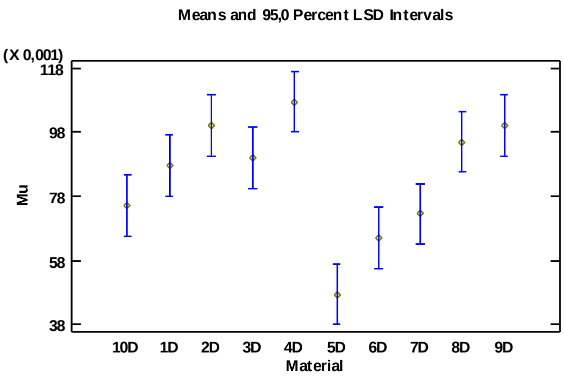

Fig.12. *Mean values with confidence limits*

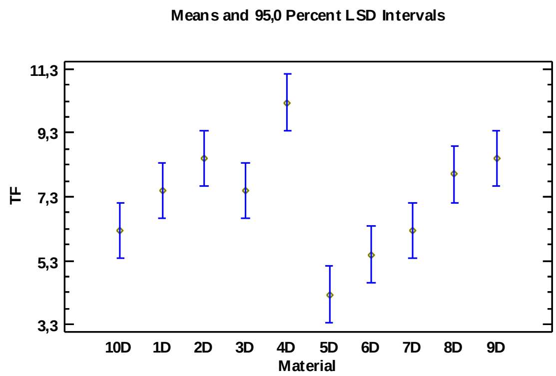

Fig.13. *Mean values with confidence limits*

With regard to censorship of data, the same reasoning as the previous variable coefficient of dry friction (Table 2) can be carried out. The friction force is considered a random magnitude and it is necessary to determine the probability distribution.

One-way ANOVA: Analysis of the factor "material"

The factors are studied separately: material (wt% CNTs) and normal test load. The dependent variable is the friction force. It is necessary to establish that the factors have a response to the dependent variable. According to Table 2, the 40 observations and the 10 levels of the material factor were examined. Average values with their confidence intervals are shown in the following figure (Figure 14). Materials 4D and 5D are different from others.

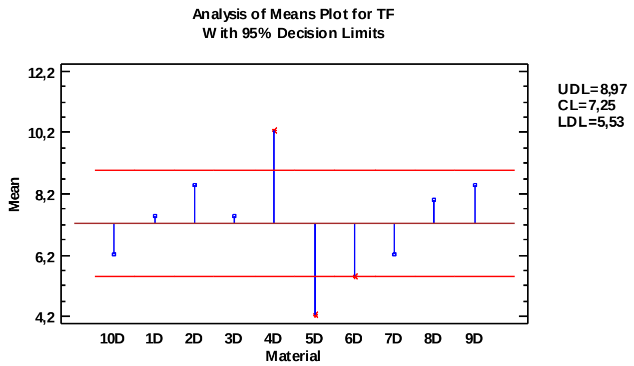

Fig.14. *Analysis of the mean values*

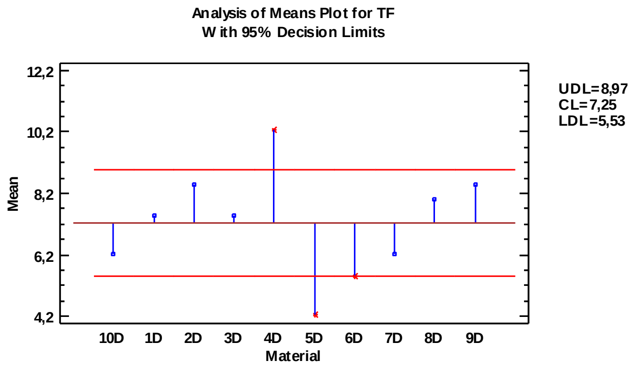

Fig.15. *Mean values for "material" factor and their location versus decision boundaries*

If the factor "material 5D" is censored, the influence of the factor on the variable "friction force" is distinct - materials 4D, 6D.

Two-factor ANOVA

The co-influence of factors: "material" and "normal load" on the variable "friction force" is investigated by two-factor analysis. The Table of Dispersion Analysis shows the simultaneous impact of both factors.

3. CONCLUSION

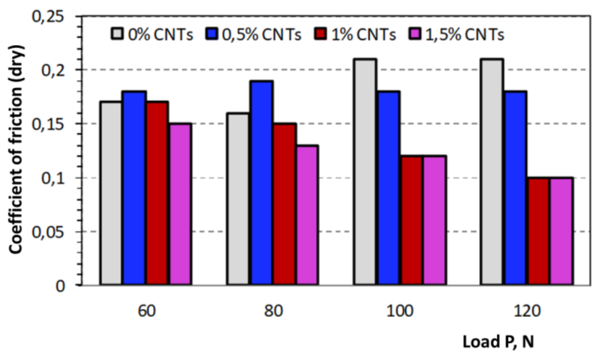

Fig.16. *Friction coefficient diagram for lubrication for the same load P at a different percentage of carbon nanotubes without nickel coating*

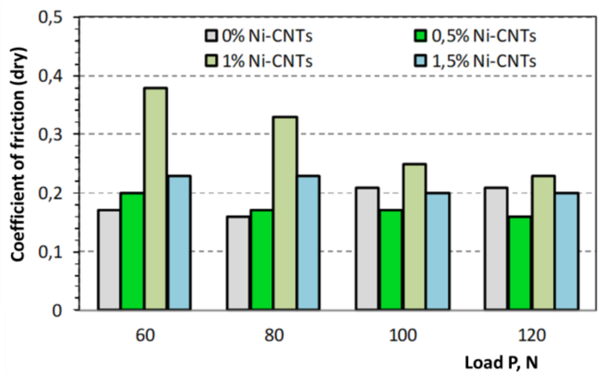

Fig.17. *Friction coefficient coefficient of the lubricant for the same load P at a different percentage of carbon nanotubes with nickel coating*

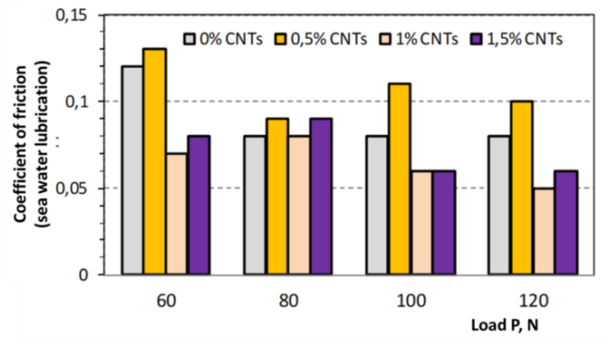

Fig.18. *Diagram of the coefficient of friction in the boundary sea water lubrication regimes for the same load P at different percentages of carbon nanotubes without nickel coating*

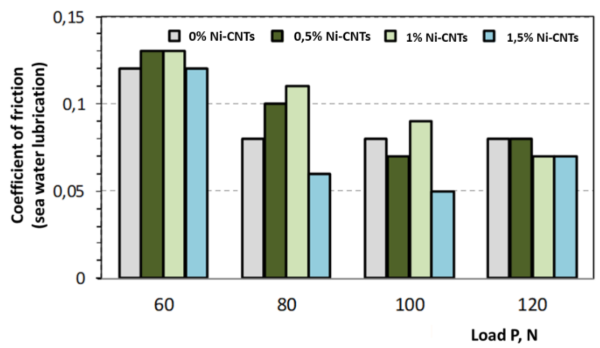

Fig.19. *Diagram of the coefficient of friction in the boundary sea water lubrication regimes for the same load P at different percentages of carbon nanotubes with nickel coating*

It can be seen from the diagrams in Figures 16, 17, 18 and Figure 19 that with the increase in the load on non-nanoparticulate materials the coefficient increases with increasing load. This is explained by an increase in the friction adhesion component as a result of an increase in the number of contact spots and the actual contact area at high contact pressure. With a low nanoparticle content of 0.5% without and with nickel coating, the friction coefficient has a persistent character, i.e. it has almost identical values for different loads, but its value is greater for nanoparticulate nickel-plated materials. With a nanoparticle content of 1% and 1.5%, the friction coefficient decreases with increasing the normal load. This is probably due to the increase of the deformation component and the reduction of the friction adhesion component by increasing the number of contact spots and the actual contact area at high contact pressure respectively.

From the graphs presented in the statistical analysis, it can be concluded that the best results for a non-lubricating surface friction coefficient (dry friction) exhibit samples (6D) UHMWPE-1.0CNTs and (7D) UHMWPE-1.5CNTs, which completely matches the results of tribological research.

From the graphs presented in the statistical analysis, it can be concluded that the best results for the coefficient of friction at sea water boundary lubrication exhibit samples (6D) UHMWPE-1.0CNTs and (10D) UHMWPE-1.5Ni-CNTs, which completely coincides with the results obtained from the tribological tests.

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