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STATISTICAL ANALYSIS OF TRIBOLOGICAL STUDY RESULTS OF ABRASIVE WEAR WITH SEA WATER AS LUBRICANT OF ULTRA-HIGH-MOLECULAR-WEIGHT POLYETHYLENE (UHMWPE), MODIFIED WITH CARBON NANOTUBES (CNTS)

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Abstract: *This article deals with the statistical analysis of tribological results of Ultra-high-molecular-weight polyethylene (UHMWPE) samples containing different concentrations of multi-walled carbon nanotubes (CNTs) - 0.5%, 0.75%, 1% and 1.5% in several instances of contact interaction with the counterpart in the case of wet abrasive wear.*
Keywords: *abrasive wear, UHMWPE, carbon nanotubes, composite materials, statistical analysis*

1. INTRODUCTION

Abrasive wear is investigated with the device schematically represented in Figure1. The contact system "*Specimen-Rotary Disc*" is placed in a seawater bath with a water level about 3÷5 mm above the level of the waterproof abrasive surface. [2,3] The experiment parameters identical for all tested samples are presented in Table 1.

Table 1.
Experiment parameters

№	Parameter	Value
1	Load	P = 60 N
2	Nominal contact area	A_a = 144 mm^2
3	Nominal contact pressure	p_a= 4.17 N/cm^2
4	Speed of rotation	n = 94 min^{-1}
5	Distance between the axis of rotation and the center of the contact	R_c = 85 mm
6	Sliding speed of the center contact	V_C = 0.9 m/s
7	Water-resistant abrasive surface	Corundum P120
8	Ambient temperature	T = 23°C

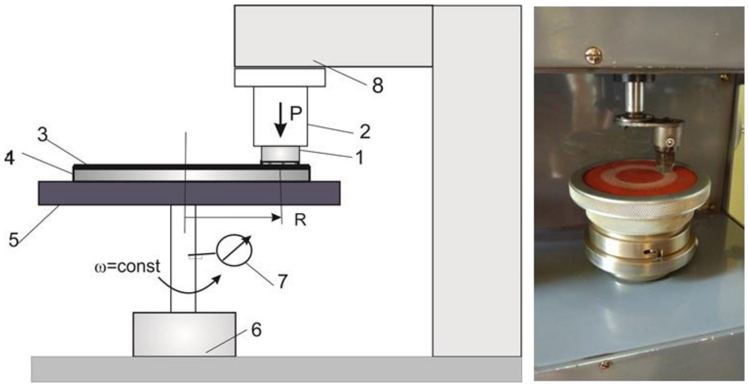

Fig.1. *Diagram of an apparatus for the study of the wear by friction on a surface with fixed abrasive scheme «Thumb-disk»*

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The chemical composition of sea water, which is taken from Sozopol, the Black Sea, used in the current experimental work is presented in Table 2.

Table 2.

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 Carbon Nanotubes used in the study are with an average diameter of 10÷40 nm, length of 1÷25 μm, purity by weight 93% and specific surface 150÷250 m^2/g. In order to improve their reinforcement properties, a surface electroless nickel plating (Ni-P) on SiC particles in alkaline bath using two nickel salts ($NiSO_4$ and $NiCl_2$) is conducted [1]. With the described methodology and device, all materials were tested for the same friction modes. Table 2, Table 3 and Table 4 show results respectively for mass wear, wear rate and wear intensity, and wear-resistance of all tested samples for different number of cycles (friction path) - N_1 = 940, N_2 = 1880, N_3 = 2820, respectively the friction path S_1 = 470, S_2 = 940 и S_3 = 1410 m. Tables 5 and 6 show results for the absolute and relative wear-resistance of the samples for the respective number of cycles (friction path).

Table 2.

Mass wear of the samples under a different friction path (number of cycles)

№	Materials	Friction time, min/number of cycles		
		10/N_1=940	20/N_2=1880	30/N_3=2820
		Wear path, m		
		470	940	1410
		Mass wear, mg		
1B	Tufnol	289.6	341.7	428.4
2B	UHMWPE-0CNTs	150.3	216.8	288.5
3B	UHMWPE-0CNTs*	203.6	230.4	243.0
4B	UHMWPE-0.5CNTs	156.5	179.2	223.8
5B	UHMWPE-0.75CNTs	81.3	108.6	155.4
6B	UHMWPE-1.0CNTs	68.4	92.5	100.5
7B	UHMWPE-1.5CNTs	209.4	216.2	222.0
8B	UHMWPE-0.5Ni-CNTs	79.5	184.7	186.9
9B	UHMWPE-1.0Ni-CNTs	85.7	99.4	113.1
10B	UHMWPE-1.5Ni-CNTs	28.3	39.6	158.6

Table 3.

Wear rate of the samples at different friction paths (number of cycles)

№	Materials	Friction time, min/number of cycles		
		$10/N_1$=940	$20/N_2$=1880	$30/N_3$=2820
		Wear path, m		
		470	940	1410
		Wear rate, mg		
1B	Tufnol	29.0	17.1	14.3
2B	UHMWPE-0CNTs	15.0	10.8	9.6
3B	UHMWPE-0CNTs*	20.4	11.5	8.1
4B	UHMWPE-0.5CNTs	15.7	9.0	7.5
5B	UHMWPE-0.75CNTs	8.1	5.4	5.2
6B	UHMWPE-1.0CNTs	6.8	4.6	3.4
7B	UHMWPE-1.5CNTs	20.9	10.8	7.4
8B	UHMWPE-0.5Ni-CNTs	8.0	9.2	6.2
9B	UHMWPE-1.0Ni-CNTs	8.6	5.0	3.8
10B	UHMWPE-1.5Ni-CNTs	2.8	2.0	5.3

Table 4.

Wear intensity of the specimens at different friction paths (number of cycles)

№	Materials	Friction time, min/number of cycles		
		$10/N_1$=940	$20/N_2$=1880	$30/N_3$=2820
		Wear path, m		
		470	940	1410
		Wear intensity, m/m		
1B	Tufnol	3.06×10^{-6}	1.8×10^{-6}	1.51×10^{-6}
2B	UHMWPE-0CNTs	2.37×10^{-6}	1.71×10^{-6}	1.5×10^{-6}
3B	UHMWPE-0CNTs*	3.21×10^{-6}	1.81×10^{-6}	1.3×10^{-6}
4B	UHMWPE-0.5CNTs	2.46×10^{-6}	1.41×10^{-6}	1.2×10^{-6}
5B	UHMWPE-0.75CNTs	1.3×10^{-6}	0.85×10^{-6}	0.81×10^{-6}
6B	UHMWPE-1.0CNTs	1.08×10^{-6}	0.73×10^{-6}	0.53×10^{-6}
7B	UHMWPE-1.5CNTs	3.3×10^{-6}	1.7×10^{-6}	1.2×10^{-6}
8B	UHMWPE-0.5Ni-CNTs	1.2×10^{-6}	1.45×10^{-6}	0.98×10^{-6}
9B	UHMWPE-1.0Ni-CNTs	1.35×10^{-6}	0.78×10^{-6}	0.59×10^{-6}
10B	UHMWPE-1.5Ni-CNTs	0.45×10^{-6}	0.31×10^{-6}	0.83×10^{-6}

Table 5.

Wear-resistance of samples at different friction paths (number of cycles)

№	Materials	Friction time, min/number of cycles		
		$10/N_1$=940	$20/N_2$=1880	$30/N_3$=2820
		Wear path, m		
		470	940	1410
		Wear resistance, m/m		
1B	Tufnol	3.2×10^{5}	5.6×10^{5}	6.6×10^{5}
2B	UHMWPE-0CNTs	4.2×10^{5}	5.8×10^{5}	6.7×10^{5}
3B	UHMWPE-0CNTs*	3.1×10^{5}	5.5×10^{5}	7.6×10^{5}
4B	UHMWPE-0.5CNTs	4.1×10^{5}	7.1×10^{5}	8.3×10^{5}
5B	UHMWPE-0.75CNTs	7.7×10^{5}	11.8×10^{5}	12.3×10^{5}
6B	UHMWPE-1.0CNTs	9.3×10^{5}	13.6×10^{5}	18.9×10^{5}
7B	UHMWPE-1.5CNTs	3.0×10^{5}	5.9×10^{5}	8.3×10^{5}
8B	UHMWPE-0.5Ni-CNTs	8.3×10^{5}	6.9×10^{5}	10.2×10^{5}
9B	UHMWPE-1.0Ni-CNTs	7.4×10^{5}	12.8×10^{5}	16.9×10^{5}
10B	UHMWPE-1.5Ni-CNTs	22.2×10^{5}	32.2×10^{5}	12.0×10^{5}

Table 6.

Relative wear-resistance

№	Materials	Wear resistance for S = 1410 m	Relative wear resistance $R_{i,j}$				
			Influence of nanoparticles on UHMWPE		Comparison UHMWPE to Tufnol		Comparison UHMWPE w/o and w/ Ni
			w/o Ni	w/ Ni	w/o Ni	w/ Ni	
1B	Tufnol	6.6 x 10^5	-	-	$R_{1,1}$=1	$R_{1,1}$=1	-
2B	UHMWPE-0CNTs	6.7 x 10^5	-	-	$R_{2,1}$=1.02	-	-
3B	UHMWPE-0CNTs*	7.6 x 10^5	$R_{3,3}$=1	$R_{3,3}$=1	$R_{3,1}$=1.2	-	-
4B	UHMWPE-0.5CNTs	8.3 x 10^5	$R_{4,3}$=1.09	-	$R_{4,1}$=1.26	-	$R_{4,4}$=1
5B	UHMWPE-0.75CNTs	12.3 x 10^5	$R_{5,3}$=1.62	-	$R_{5,1}$=1.86	-	-
6B	UHMWPE-1.0CNTs	18.9 x 10^5	$R_{6,3}$=2.49	-	$R_{6,1}$=2.86	-	$R_{6,6}$=1
7B	UHMWPE-1.5CNTs	8.3 x 10^5	$R_{7,3}$=1.09	-	$R_{7,1}$=1.26	-	$R_{7,7}$=1
8B	UHMWPE-0.5Ni-CNTs	10.2 x 10^5	-	$R_{8,3}$=1.34	-	$R_{8,1}$=1.55	$R_{8,4}$=1.23
9B	UHMWPE-1.0Ni-CNTs	16.9 x 10^5	-	$R_{9,3}$=2.22	-	$R_{9,1}$=2.56	$R_{9,6}$=0.89
10B	UHMWPE-1.5Ni-CNTs	12.0 x 10^5	-	$R_{10,3}$=1.6	-	$R_{10,1}$=1.8	$R_{10,7}$=1.4

2. STATISTICAL ANALYSIS OF THE OBTAINED RESULTS

The following variables are introduced [4÷8]:

Variable	Description	Dimensions
m	numerical variable: mass wear	[mg]
Gamma	numerical variable: wear rate	[mg/min]
i	numerical variable: wear intensity	[micro g/m]
II	numerical variable: wear-resistance	[m/micro g]
Rij_CN_UH_sw	numerical variable: relative wear-resistance	[.]
Rij_UH_Tf_sw	numerical variable: relative wear-resistance	[.]
Material_LL	grouping variable: (string)	
Time	groupsing variable: friction time (min/cycles) (integer)	
	10/N_1=940 · 20/N_2=1880 · 30/N_3=2820	
S	grouping variable: friction path (integer)	
	470 · 940 · 1410	
Ni_CN_UH	grouping variable: 0 – without Ni, 1 – with Ni	
Ni_UH_Tf	grouping variable: 0 – without Ni, 1 – with Ni	

Material_LL grouping variable (string)	**Material**	**Material_1 grouping variable (integer)**
1**B**	Tufnol	1
2**B**	UHMWPE-0CNTs	2
3**B**	UHMWPE -0CNTs*	3
4**B**	UHMWPE -0.5CNTs	4
5**B**	UHMWPE -0.75CNTs	5
6**B**	UHMWPE -1.0CNTs	6
7**B**	UHMWPE -1.5CNTs	7
8**B**	UHMWPE -0.5Ni-CNTs	8
9**B**	UHMWPE -1.0Ni-CNTs	9
10**B**	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: Analysis of the factor "material"

The factors are studied separately: material wt% CNTs), number of cycles in the tests, distance. The dependent variable is mass wear. It is necessary to establish that the factors have a response to the dependent variable. According to Table 2, the 30 observations and the 10 levels of the factor "material" are examined. The mean values with their confidence intervals are shown in Figure 2: Number of observations: 30 and Number of Factor Levels: 10

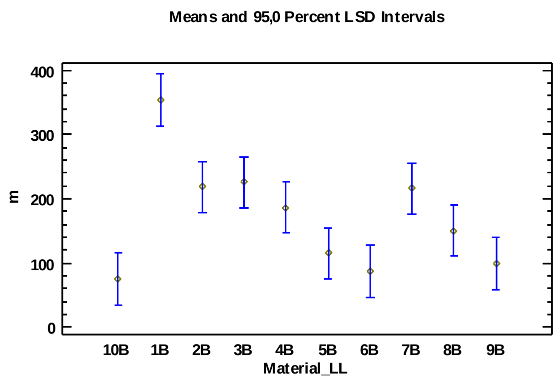

Fig.2. *Mean values and confidence intervals*

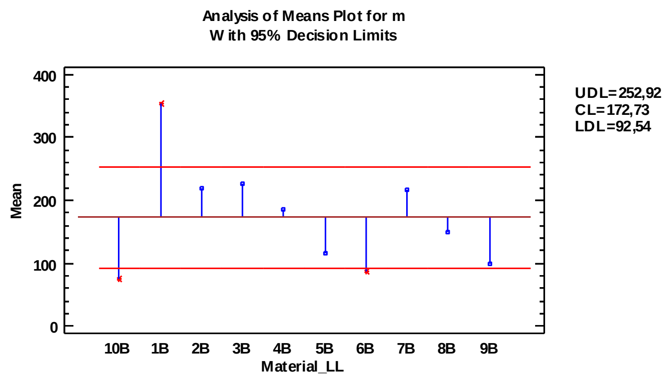

Fig.3. *Investigation of mean values and confidence limits*

The analysis of the mean values (Figure 3) shows the influence of the factor on the wear. Materials 1B, 10B and 6B are different from others. If data is censored and Material 1B is removed from the examination, the other wear materials may be represented by the following graphs:

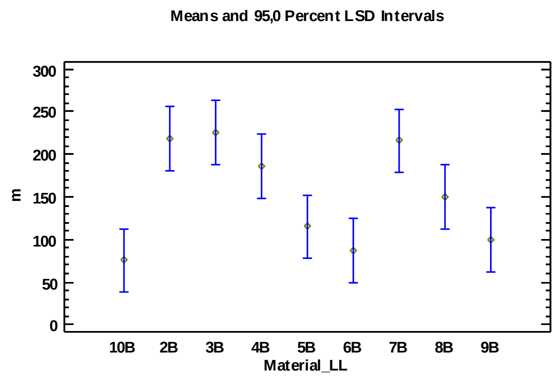

Fig.4. *Average values of censored data*

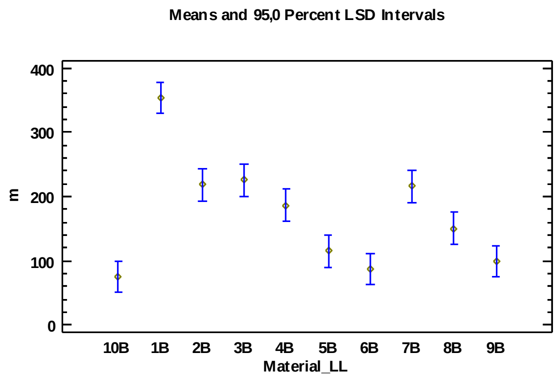

Fig.5. *Mean values with confidence limits*

A response is observed with respect to material 10B. In this case, the analysis shows a tendency towards 2B, 3B, 4B, 5B, and 6B, as well as materials 7B, 8B and 9B.

Multi-factor ANOVA: Wear rate of the test samples

The co-influence of factors: "material" and "friction time" on the variable mass wear is investigated by two-factor analysis. In the one-way analysis, the influence of the "friction time" factor is not clearly emphasized. With regard to censorship of data, the same reasoning as the previous variable mass wear (Table 3). The wear rate 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), number of test cycles, distance. The dependent variable is the wear rate. It is necessary to establish that the factors have a response to the dependent variable. According to Table 3, the 30 observations and the 10 levels of the factor "material" are examined. The mean values with their confidence intervals are shown in Figure 6.

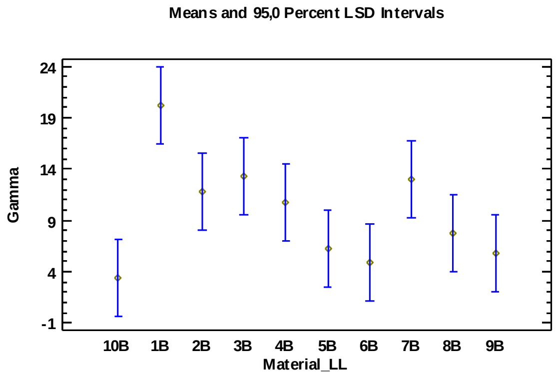

Fig.6. *Mean values with confidence limits*

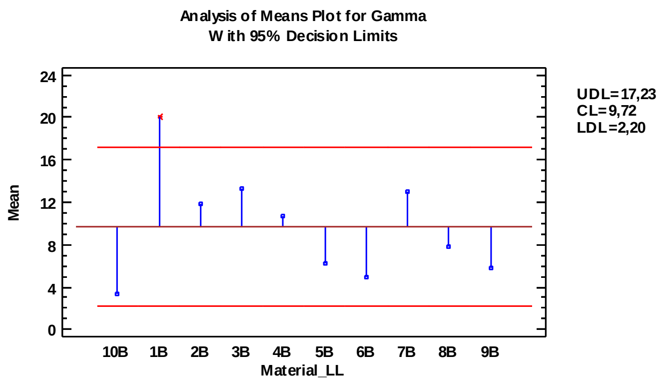

Fig.7. *Analysis of the mean values*

Material 1B (Tufnol) again has a substantial response to "wear rate" (Figure 6 and Figure 7). Two trends can be noticed – materials 1B÷6B and materials 7B, 8B and 9B. Material 1B is significantly different. If the material factor is censored, the response (influence) of the factor on the variable "wear velocity" is unclear. On the other hand, the "friction time" and "friction path" factors show a clear response. This is the reason to directly switch to two-factor data analysis.

Two-way ANOVA: Intensity of wear of the samples

The joint influence of factors: "material" and "friction time", as well as the "friction path" factor, on the variable "wear rate" is investigated by two-factor analysis.

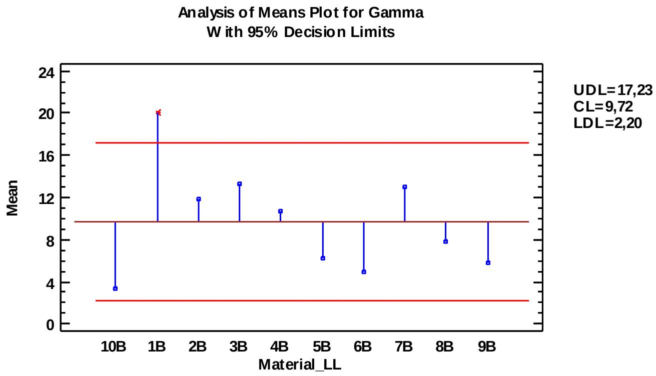

Fig.8. *Mean values for factor "material" and their location versus decision boundaries*

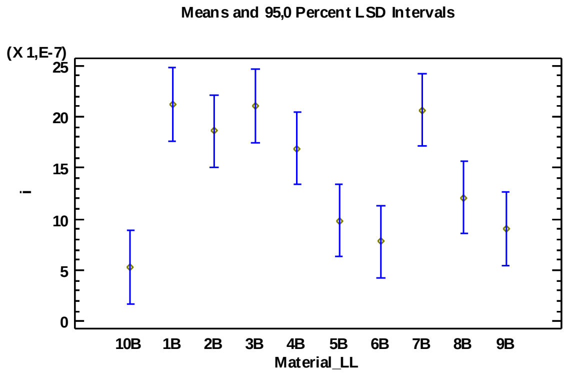

Fig.9. *Mean values and confidence intervals*

The "friction path" factor study results in the same results as "friction time". Both factors are linearly dependent and as such can not be used for analysis. With regard to censorship of data, the same reasoning as the previous variable mass wear can be made (Table 4). The wear intensity is considered a random magnitude and it is necessary to determine the probability distribution.

Two-way ANOVA: Wear-resistance of the test speciments

The joint influence of factors "material" and "friction time" on the variable "wear intensity" is investigated by two-factor analysis. In the one-factor analysis, the influence of the "friction time" factor is clearly highlighted, but for the "material" factor it is not fulfilled. Again, there are two parallel trends in the plurality of materials. Both factors: "material" and "friction time" affect the accidental wear intensity variable. P-Values prove this conclusion. Once again, it can be stressed that the two "material" and "friction times" factors, due to the correct experiment, influence the variable "wear intensity".

3. CONCLUSION

At a nanoparticle content of 5.0 and 1.5%, a high degree of resistance is provided when leaving non-nickel coated nanoparticles. Comparative results for the wear-resistance of nanoparticulate materials with and without nickel coating are presented in the last column of Table 6.

The dependence of the wear-resistance on the percentage of carbon nanotubes with and without nickel coating has a very non-linear wavy character, unlike that of dry abrasive friction. It has a pronounced maximum for both types of nanoparticles at 1% nanoparticle content - Figure 10.

With higher carbon nanotubes, the wear-resistance decreases for both nanotubes, with lower wear-resistance for nanoparticles without nickel coating.

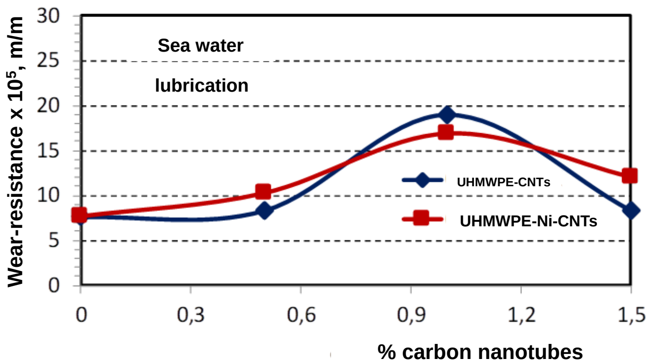

Fig.10. *Dependence of wear resistance from the percentage of nanoparticles for UHMWPE materials, with and without nickel coating*

Figure 11 and Figure 12 show diagrams of the absolute and relative wearing resistance of all tested samples.

Clearly, we can see that most wear-resistive sample is (UHMWPE-1.0CNTs) with 1% nanoparticles without nickel coating - $I=18.9x10^5$, which is 2.3 $x10^5$ greater than that of samples with the same percentage of nanoparticles, but with nickel coating (UHMWPE-1.0Ni-CNTs) - $I=16.9x10^5$.

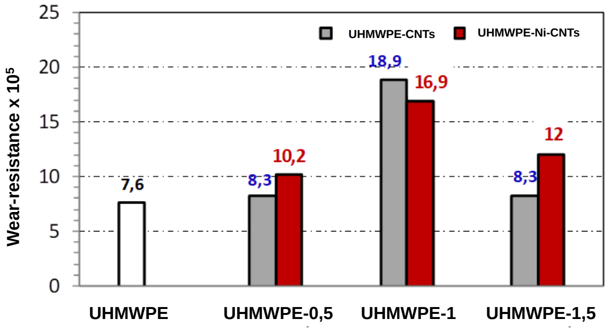

Fig.11. *Diagram of the wear-resistance of UHMWPE materials with carbon nanotubes with and without nickel plating for N=400*

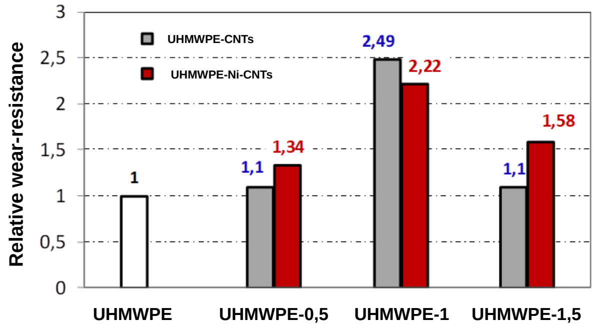

Fig.12. *Diagram of the relative wear-resistance of UHMWPE materials with carbon nanotubes with and without nickel plating for N=400*

Wear-resistance is a reciprocal value of variable wear intensity. The results are identical with those obtained for "wear intensityFor the influence of the factors: "material", "friction time" and "friction path", the following conclusions can be drawn:

- All data is used to highlight the influence of factors on samples: 1B÷10B. Materials 10B and 6B differ from others;

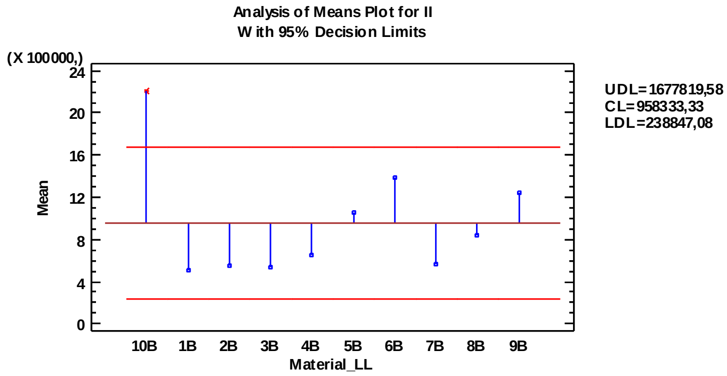

Fig.13. *Graphical representation of the mean values for the factor "material"*

From the graphs presented in the statistical analysis it can be concluded that the best results for abrasive wear during sea water lubrication exhibits sample (6B) UHMWPE-1.0CNTs, which fully coincides with the results obtained from the tribological tests. The presented model fully justifies the experiment under consideration.

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