Годишник на Технически Университет - София, том 69, книга 2, 2019
Proceedings of the Technical University of Sofia, Volume 69, Issue 2, 2019

STATISTICAL ANALYSIS OF TRIBOLOGICAL STUDY RESULTS OF BOUNDARY FRICTION WITH MARINE OIL 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 the results of a tribological study of the wear-resistance of Ultra-High-Molecular-Weight Polyethylene (UHMWPE) samples containing a different concentration of carbon nanotube additive (CNTs): 0.5%, 0.75%, 1.0% and 1.5% in several cases of contact interaction with the counter-body under conditions of boundary friction with marine oil.*
Keywords: *boundary friction, UHMWPE, carbon nanotubes, composite materials, marine oil, statistical analysis*

1. INTRODUCTION

Friction and wear in the presence of lubricants are complex processes that are highly dependent on physico-chemical and mechanical contact interactions between the lubricant environment and the surface layers of the contacting bodies.

These processes also depend on the modes of operation - load, speeds, presence of dynamic disturbances (vibrations). In machines the contact fittings operate in different friction modes - fluid, mixed, boundary and dry friction. None of them is in pure form. In the time and in the spatial distribution of processes in the tribosystems the mixed friction is most often encountered - the presence of discrete contact areas of the microgrades, areas with the presence of a lubricating layer and areas in which touching is performed by thin lubricating layers and films. Friction friction is the heaviest friction mode that is almost inevitable in all contact fittings in machines.

The wear test device for border friction in lubricating environment has been developed in the tribology laboratory. The functional diagram of the device is shown in Figure 1. The tribological contact is point and occurs between the test specimen 2 and a spherical indentor (counter) 1 with a diameter of 5 mm fixed in the holder 3. The indentor 1 rotates about its vertical axis at a constant angular velocity.

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]

ISSN 1311-0829

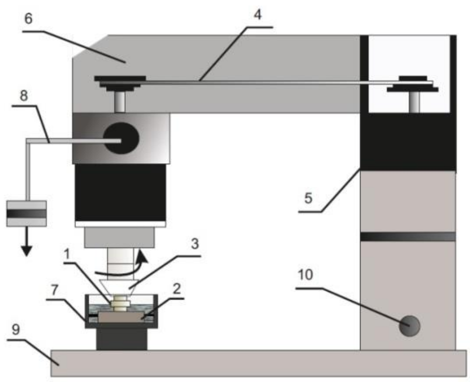

Fig.1 *Diagram of device for examination of wear in border friction in lubricating environment: 1-spherical indentor; 2-sample; 3-holder of the indentor; 4-belt drive; 5-electric motor; 6-housing; 7-bathtub; 8-lever loading system; 9-base of the housing; 10-button for switching on the electric motor.*

The drive of the holder 3, respectively, of the indentor 1, is effected by an electric motor 5 and a belt drive 4. Changing the angular velocity is done by changing the rotational speed using the belt drive 4. In this way, the desired speed of sliding friction can be set. The device allows variation in rotation speeds up to 4000 rpm. The sample 2 is placed horizontally in the bath 7 with lubricant, in this case marine oil. The normal load P in the center of the indentor is set by weights with lever system 8. The device works in the following sequence: The test specimen 1 is fastened to the holder 3 and the counter body is placed and fixed horizontally to the holder in the bath 7. Load P is set by the weight of the arm 8 from the lever system. In the tub 7, lubricant is placed at a level up to 5 mm above the level of the counter body 2. The temperature of the lubricant is measured. The desired rotation speed is set with the belt drive 4. With the button 10 the electric motor is switched on and the time of friction or speed counter is measured with a stopwatch. After a certain friction time the motor is stopped and the temperature of the lubricant material in the tub is measured again. The methodology for the study of wear is based on measuring the maximum value of the linear wear CD=h after a certain friction time and calculation of the volumetric wear V (Figure 2).

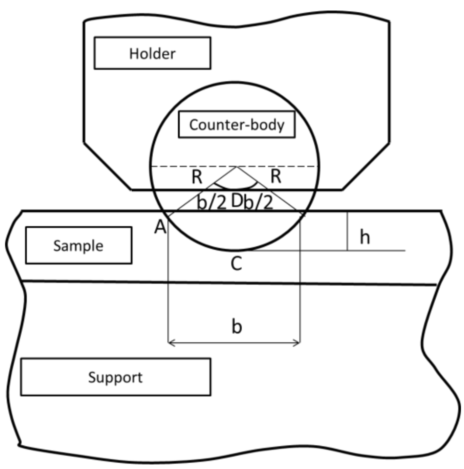

Fig.2. *Maximum linear wear of a spherical indentor sample*

In the present study, ship oil with the abbreviation M1 (MC 20) is used. The study was conducted under the experimental conditions presented in Table 1.

Table 1.
Experiment Parameters

№	Parameter	Value
1	Load	P = 20 N
2	Nominal contact area	A_a = 144 mm^2
3	Nominal contact pressure	p_a= 13,89 N/cm^2
4	Speed of rotation	n = 750 min^{-1}
5	Friction time	t = 20 min
6	Ambient temperature	T = 23°C
7	Initial oil temperature	T_M = 23°C

Table 2, Table 3 and Table 4 show results for linear and volumetric wear, speed and wear intensity, absolute and relative wear-resistance of the tested materials when lubricated with oil M1, determined according to the described methodology.

Table 2.
Linear and volumetric wear when lubricating with oil M1

№	MATERIALS	Linear Wear, µm						Volumetric wear, mm^3
		h_1	h_2	h_3	h_4	h_5	h	
1C	Tufnol	152	160	158	150	165	157	190 x 10^{-3}
2C	UHMWPE-0CNTs	110	115	118	120	122	117	105 x 10^{-3}
3C	UHMWPE-0CNTs*	75	80	82	70	84	78.2	47 x 10^{-3}
4C	UHMWPE-0.5CNTs	80	85	90	92	87	86.2	57 x 10^{-3}
5C	UHMWPE-0.75CNTs	102	95	110	98	105	102	81 x 10^{-3}
6C	UHMWPE-1.0CNTs	105	100	92	95	90	96.4	71 x 10^{-3}
7C	UHMWPE-1.5CNTs	54	50	65	58	70	59.4	27 x 10^{-3}
8C	UHMWPE-0.5Ni-CNTs	135	140	142	145	130	138.4	147 x 10^{-3}
9C	UHMWPE-1.0Ni-CNTs	110	115	105	120	125	115	102 x 10^{-3}
10C	UHMWPE-1.5Ni-CNTs	65	70	72	68	75	70	38 x 10^{-3}

Table 3.
Speed, intensity and wear resistance when lubricating with oil M1

№	Materials	Wear Rate µm/min	Wear Intensity mm^3/cycle	Wear-resistance, cycles/mm^3
1C	Tufnol	7.85	1.27 x 10^{-5}	7.9 x 10^4
2C	UHMWPE-0CNTs	5.85	0.7 x 10^{-5}	14.3 x 10^4
3C	UHMWPE-0CNTs*	3.91	0.3 x 10^{-5}	33.3 x 10^4
4C	UHMWPE-0.5CNTs	4.31	0.38 x 10^{-5}	26.3 x 10^4
5C	UHMWPE-0.75CNTs	5.1	0.5 x 10^{-5}	20 x 10^4
6C	UHMWPE-1.0CNTs	4.82	0.4 x 10^{-5}	25 x 10^4
7C	UHMWPE-1.5CNTs	2.97	0.18 x 10^{-5}	55.6 x 10^4
8C	UHMWPE-0.5Ni-CNTs	6.92	0.98 x 10^{-5}	10.2 x 10^4
9C	UHMWPE-1.0Ni-CNTs	5.75	0.68 x 10^{-5}	14.7 x 10^4
10C	UHMWPE-1.5Ni-CNTs	3.75	0.25 x 10^{-5}	40 x 10^4

Table 4.

Relative wear-resistance when lubricating with oil M1

№	MATERIALS	Wear-re-sistance cycles/mm^3	Relative wear-resistance $R_{i,j}$				
			Influence of nanoparti-cles on UHMWPE		Comparison of UHMWPE and Tufnol		Compari-son of UHMWPE without Ni and with Ni
			without Ni	with Ni	without Ni	with Ni	
1C	Tufnol	7.9 x 10^4	-	-	$R_{1,1}$=1	$R_{1,1}$=1	-
2C	UHMWPE-0CNTs	14.3 x 10^4	-	-	$R_{2,1}$=1.8	-	-
3C	UHMWPE-0CNTs*	33.3 x 10^4	$R_{3,3}$=1	$R_{3,3}$=1	$R_{3,1}$=4.2	-	-
4C	UHMWPE-0.5CNTs	26.3 x 10^4	$R_{4,3}$=0.8	-	$R_{4,1}$=3.3	-	$R_{4,4}$=1
5C	UHMWPE-0.75CNTs	20.0 x 10^4	$R_{5,3}$=0.6	-	$R_{5,1}$=2.5	-	-
6C	UHMWPE-1.0CNTs	25.0 x 10^4	$R_{6,3}$=0.8	-	$R_{6,1}$=3.2	-	$R_{6,6}$=1
7C	UHMWPE-1.5CNTs	55.6 x 10^4	$R_{7,3}$=1.7	-	$R_{7,1}$=7.0	-	$R_{7,7}$=1
8C	UHMWPE-0.5Ni-CNTs	10.2 x 10^4	-	$R_{8,3}$=0.3	-	$R_{8,1}$=1.3	$R_{8,4}$=0.4
9C	UHMWPE-1.0Ni-CNTs	14.7 x 10^4	-	$R_{9,3}$=0.4	-	$R_{9,1}$=1.9	$R_{9,6}$=0.6
10C	UHMWPE-1.5Ni-CNTs	40.0 x 10^4	-	$R_{10,3}$=1.2	-	$R_{10,1}$=5.1	$R_{10,7}$=0.7

2. STATISTICAL ANALYSIS OF THE OBTAINED RESULTS

The following variables are introduced [2÷6]:

Variable	Description	Dimension
mh	numerical variable: linear wear	[μm]
Vh	numerical variable: volumetric wear	[mm^3]
Gammah	numerical variable: wear rate	[mg/min]
iV	numerical variable: intensity of volumetric wear	[mm^3/N]
Ih	numerical variable: wear-resistance	[m/micro g]
Rij_CN_UH_smo	numerical variable: relative wear-resistance	[.]
Rij_UH_Tf_smo	numerical variable: relative wear-resistance	[.]
N	Number of cycless	[.]
Measurement	grouping variable for linear wear on measurements (integer)	
	h1 -1 | h2 -2 | h3 -3 | h4 -4 | h5 -5	
Ni_CN_UH	grouping variable: 0 – without Ni, 1 – with Ni	
Ni_UH_Tf	grouping variable: 0 – without Ni, 1 – with Ni	

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

Each experimental 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), linear wear measurements (h_i). The dependent variable is linear wear. It is necessary to establish that the factors have a response to the dependent variable. According to Table 2, the 50 observations and the 10 levels of the factor "material" are examined. The mean values with their confidence intervals are shown in Figure 3: Number of observations: 50 (all measurements of linear wear) and Number of Factor Levels: 10.

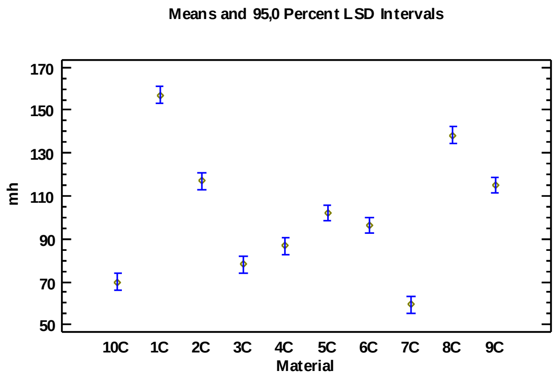

Fig.3. *Mean values and confidence intervals*

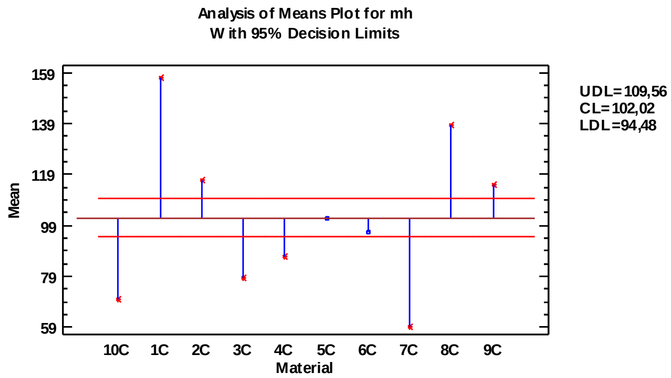

Fig.4. *Investigation of mean values and confidence limits*

The analysis of the mean values (Figure 4) shows the influence of the factor on the linear wear. Materials 1C, 7C, 8C and 10C are distinguished from the rest. If the data is censored, the material 1C of the examination is dropped, the other materials in terms of wear can be represented by the following graph (Figure 5). Again, there is a more detailed response to the rest of the materials.

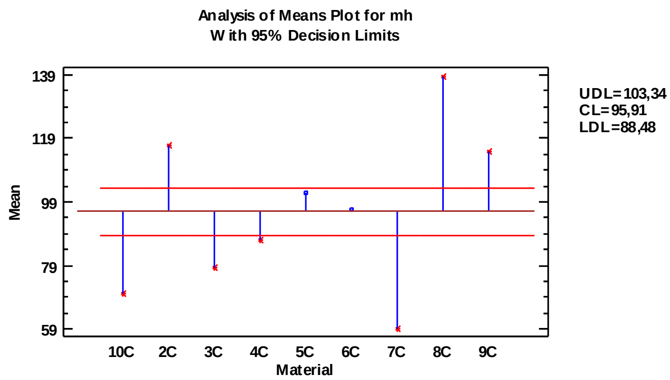

Fig.5. *Mean values and decision boundaries for deciding when an essential response to the "material" on the dependent variable*

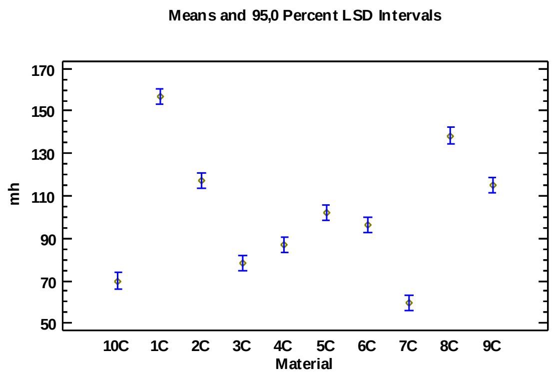

Fig.6. *Mean values with confidence limits*

Multi-factor ANOVA

The co-influence of factors: "material" and "number of measurements" on variable mass wear is examined by two-factor analysis. In the single factor analysis, the impact of the "number of measurements" factor is not clearly highlighted.

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

The factors are studied separately: material (wt% CNTs), linear wear measurements (h_i). The dependent variable is volumetric wear. It is necessary to establish that the factors have a response to the dependent variable. According to Table 2, the 50 observations and the 10 levels of the factor "material" are examined. The mean values with confidence intervals are shown in Figure 7: Number of observations: 50 (all measurements of linear wear) and Number of Factor Levels: 10.

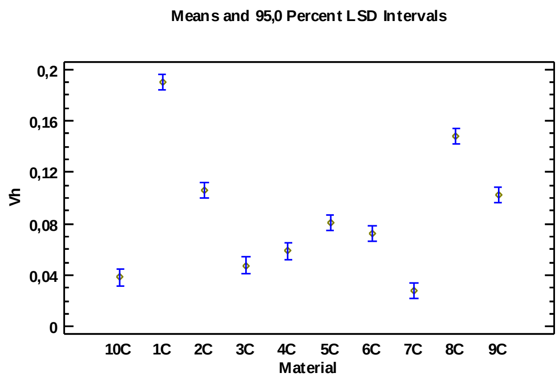

Fig.7 *Mean values and confidence intervals*

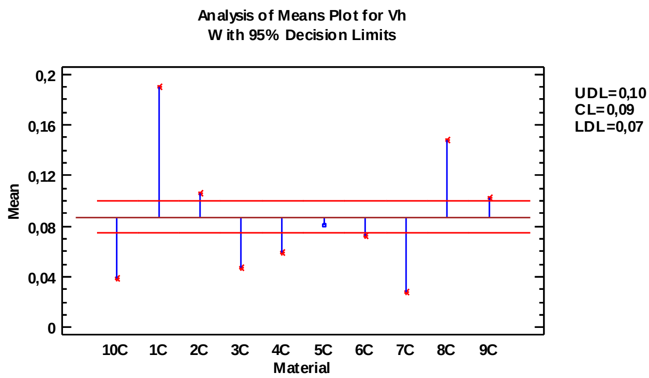

Fig.8 *Investigation of mean values and confidence limits*

The analysis of the mean values (Figure 8) shows the influence of the factor on the linear wear. Material 5C has no response to volume wear. If data is censored, material 1C is removed from the examination, the other wear materials can be represented by the following graph (Figure 9). Again, there is a more detailed response to the rest of the materials.

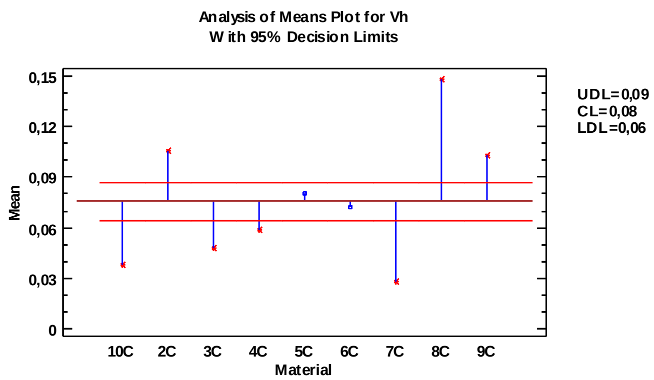

Fig.9. *Mean values and decision boundaries for an essential response of the factor "material" on the dependent variable*

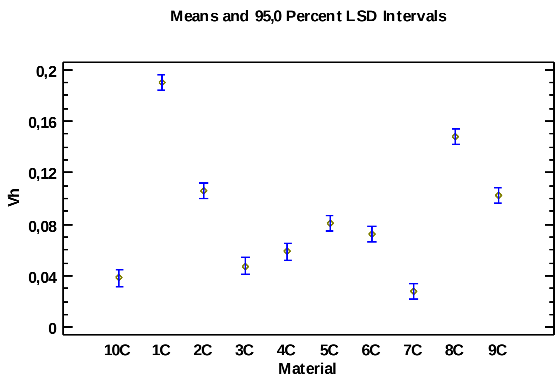

Fig.10. *Mean values with confidence limits*

Sample wear rate

Data from Table 3 are considered. Wear rate data is restored for measurements: h_1, h_2, h_3, h_4, h_5. The wear rate is considered a random variable 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 measurements h_1, h_2, h_3, h_4, h_5. 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 50 observations and the 10 levels of the factor "material" are examined. The mean values with their confidence intervals are shown in Figure 11.

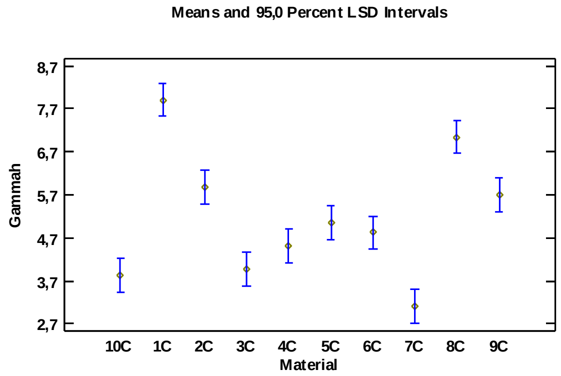

Fig.11. *Mean values with confidence limits*

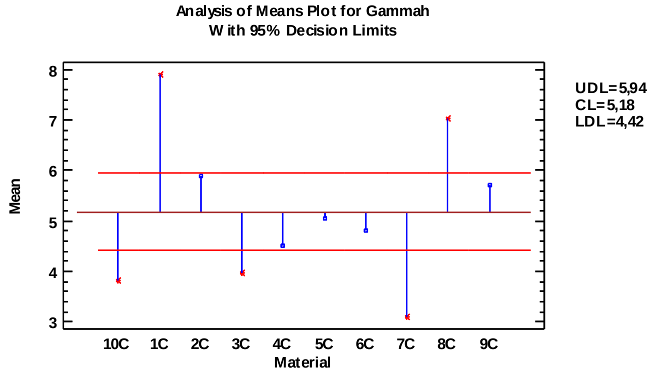

Fig.12. *Analysis of the mean values*

Materials 1C (Tufnol), 3C, 7C, 8C and 10C again have a substantial response in terms of "wear rate" (Figure 12). Factor "material" has a significant response (influence) on the variable "wear rate". Factor "Measurements" has no corresponding response to the dependent variable. This is the reason to directly switch to two-factor data analysis.

Two-factor ANOVA: Intensity of wear of the samples

The joint influence of factors: "material" and "number of measurements" on the variable "wear rate" is investigated by two-factor analysis. In the single factor analysis, the impact of the "number of measurements" factor is not clearly highlighted.

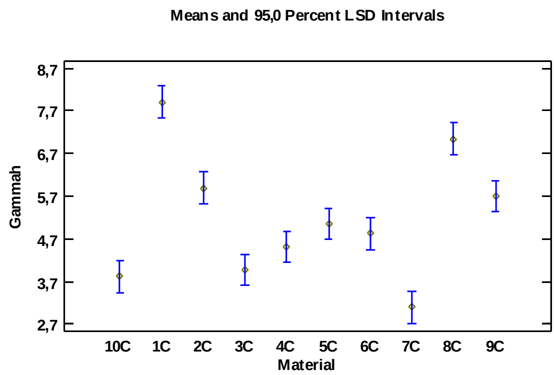

Fig.13. *Mean values and confidence limits for factor "material"*

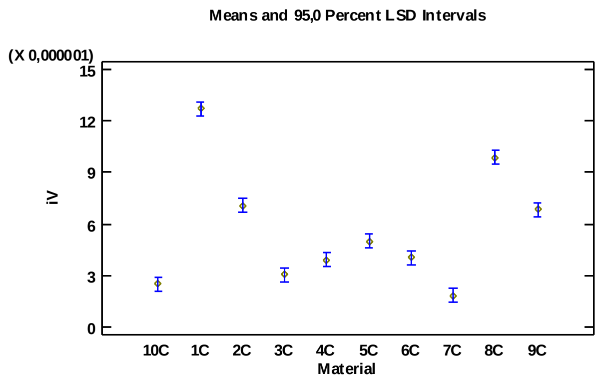

Fig.14. *Mean values and confidence intervals*

The data is presented in Table 3. The data is reconstructed on the measurements h_1, h_2, h_3, h_4, h_5. The wear intensity is considered a random magnitude and it is necessary to determine the probability distribution.

Two-factor ANOVA: Wear-resistance of the samples

The co-influence of factors: "material" and "number of defects" on the variable "wear intensity" is examined by two-factor analysis. In the single factor analysis, the influence of the number of cycles factor is not clearly highlighted. The censored values are used.

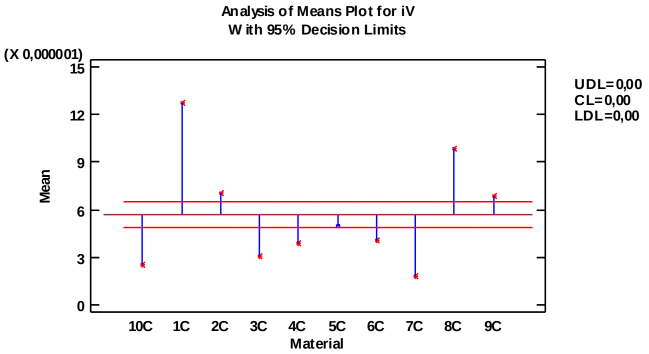

Fig.15. *Analysis of the response of mean values*

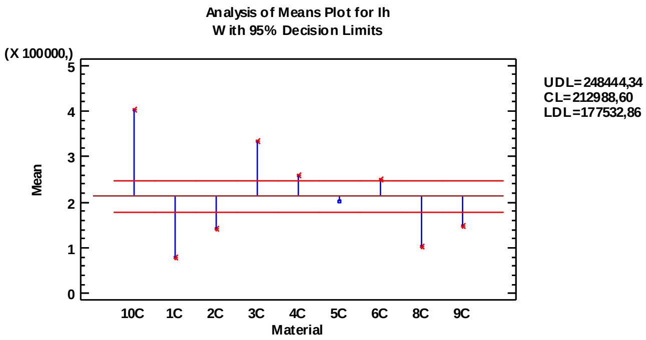

Fig.16. *A graphical representation of the mean values for the "material"*

Wear-resistance is a reciprocal value of variable wear intensity. The results are identical with those obtained for "wear intensity".

3. CONCLUSION

Figure 17 shows the graphical dependence of the sample's volumetric wear on the percentage of nickel-coated carbon nanotubes.

The dependence of wear on the percentage of nickel-coated carbon nanotubes has a strong non-linear character with a pronounced maximum in UHMWPE, doped with 0.5% carbon nanotubes with nickel coating. Nano-coated nanotubes with less nickel coating have less wear for each nanotubes.

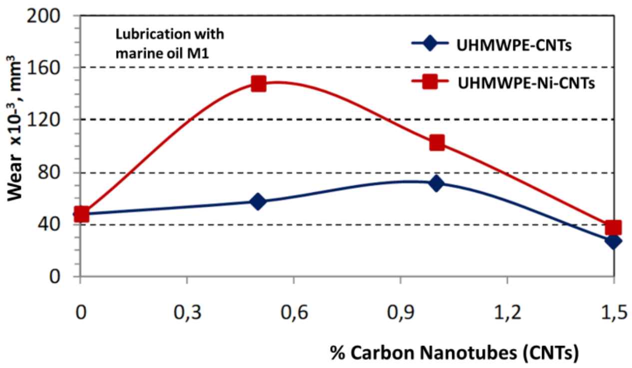

Fig.17 *Dependence of the volumetric wear of the specimens by the percentage of carbon nanotubes with and without nickel coating upon lubrication with oil M1*

Figure 18 and Figure 19 show diagrams of absolute and relative wear-resistance of UHMWPE materials with carbon nanotubes with and without nickel coating.

The relative wear-resistance of Figure 19 is shown in a reference sample UHMWPE without nanoparticles, i.e. sample №3C.

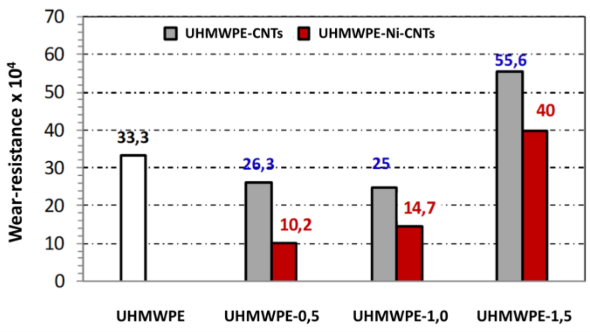

Fig.18. *Diagram of wear-resistance of UHMWPE materials with carbon nanotubes with and without nickel coating upon lubrication with oil M1*

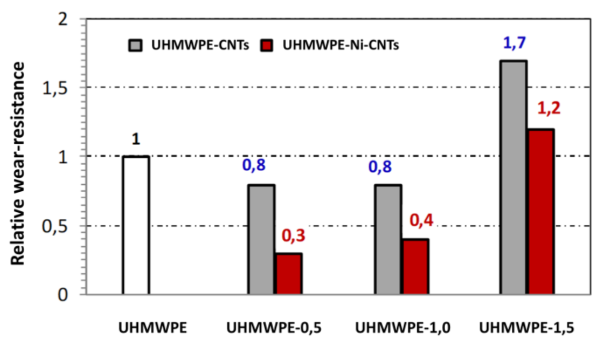

Fig.19. *Diagram of the relative wear-resistance of UHMWPE materials with carbon nanotubes with and without nickel coating upon lubrication with oil M1*

It can be seen from Figure 19 that all samples doped without nickel-plated nanotubes have a higher wear resistance than those with nickel coated nanotubes. The presence of nickel is likely to reduce cohesive strength, resulting in lower frictional tensile stresses and increased wear. The highest wear-resistance has the sample UHMWPE-1,5CNTs doped with 1.5% carbon nanotubes I=55,6x10^4 cycles/mm^3, which is about 1.4 times higher than the wearing resistance of a sample UHMWPE-1.5Ni-CNTs doped with 1.5% nickel-plated nanotubes.

For the influence of factors: "material" and "number of measurements", the following conclusions can be drawn:

- Working with actual reconstructed data to highlight the impact of factors on samples: 1C÷10C;

Of the presented graphs of statistical analysis it can be concluded that the best results for wear in boundary friction with marine oil exhibits sample (7C) UHMWPE-1.5CNTs, which fully coincides with the results obtained from the tribological tests. The presented model fully justifies the experiment under consideration.

ACKNOWLEDGEMENTS

These studies were carried out and supported by laboratory “Tribology” of the Technical University of Sofia and funded in 2019 under the Ministry of Education and Science program "*Young Scientists and Postdoctoral Candidates*", EU RESEARCH FRAMEWORK PROGRAMME Horizon 2020, National Strategy for the Development of Scientific Research in the Republic of Bulgaria 2017-2030, Innovation Strategy for Smart Specialization 2020.

REFERENCES

[1] Dimitrova R., Electroless nickel coatings on silicon carbide particles using two nickel salts in alkaline solution, International Working Conference “Total Quality Management - Advanced and Intelligent Approaches”, 2-5 June, 2015, Belgrade, Serbia

[2] Douglas C. Montgomery, George C. Runge, Applied Statistics and Probability for Engineers, John Wiley & Sons, Inc., 2011, ISBN–13: 978-0-470-05304-1.

[3] Thomas P. Ryan, Modern Engineering Statistics , John Wiley & Sons, Inc., 2007, ISBN 978-0-470-08187-7

[4] David M. Levine, Ph.D., David F. Stephan, Even You Can Learn Statistics, A Guide for Everyone Who Has Ever Been Afraid of Statistics, 2010 by Pearson Education, Inc., ISBN-10: 0-13-701059-1, ISBN-13: 978-0-13-701059-2.

[5] D. N. Lawley and A. E. Maxwell, Factor Analysis as a Statistical Method, Journal of the Royal Statistical Society. Series D (The Statistician) Vol. 12, No. 3, Factor Analysis (1962), pp. 209-229 Wiley.

[6] D. N. Lawley and A. E. Maxwell, Factor Analysis as a Statistical Method, Butterworths, London, 1963.

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