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WEAR, FRICTION COEFFICIENT AND SLIP PROPERTY ESTIMATION OF SLIDING FRICTION PARTS

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ABSTRACT

The key purpose of this work is to propose a methodology for lifetime prediction of wear parts using 3D surface roughness parameters defined in the standard ISO 25178 part 2 for wear rate determination. In this research the random surface model is used, where the height of surface asperities h(x, y) has a normal probability distribution. As a result of research the equations for estimation of the fatigue wear rate and friction coefficient were derived. Also it was revealed that 3D surface roughness parameters are more influential on linear wear rate.

In experimental part authors test practical method for static sliding friction coefficient and slip property estimation for different nanostructured coatings. Method is based on inclined plane and it is usable for wide variations of materials. 5 different titanium-containing nanocoated experimental samples were tested. In addition dynamic sliding friction coefficient and 3D surface texture parameters were measured for all samples using CSM tribometer and Taylor Hobson Forms Talysurf Intra 50 profilometer.

Index Terms - Wear, sliding friction, sliding properties, 3D roughness

1. INTRODUCTION

The present methodology of lifetime prediction of details is based on approach for fatigue wear rate determination using 2D roughness parameters. But in practical applications machine parts surface roughness behaves as a 3D object. Surface texture metrology gives a better understanding of the surface in its functional state [1]. Therefore it is necessary to create a new theoretical and practical basis for machine parts surface assessment as a 3D quantity [2, 3]. Recently a draft standard [ISO 25178-2] developed by the ISO Technical Committee proposes the definition of areal parameters as an extension of the well-known profile parameters.

However, only a few studies try to link the surface roughness with functional requirements [4-6]. Work [4] deals with the prediction of the 3D surface topography according to the machining conditions. Authors have proved that using 3D surface topography allows correctly achieve process planning and link resulting surface patterns with part functionality. In [5] it was established that the character of the machined surface is better distinguished by 3D arrangements than by 2D arrangements. 3D images and adequate contour maps of the surfaces, generated by turning, allow distinguishing mixed-anisotropic textures when the random part of the generated surface was significantly greater for the CB20 cutting tool material.

Some works were related with the study of the correlation between surface topography evaluation and frictional behaviour. For example, in [6] by examining 3D surface topography of two mating bodies, both surface roughness and its effect on friction behaviour were studied. Authors accent that 3D measurements enable evaluation of the surface information, which in turn offers increased possibilities for understanding the connections between surface topography and functional performance. In [1] was underlined, that a fundamental problem in 2D profilometry is that a profile does not necessarily indicate functional aspects of the surface. However, when the 3D surface parameters are used, it can be assumed that surface topography may have far more influence on the friction and wear behaviour.

We can conclude that in the present there is the necessity in study which will use 3D surface roughness parameters for wear, sliding friction and slip property estimation.

2. WEAR RATE AND FRICTION COEFFICIENT DETERMINATION

In this research, the random surface model is used. The surface machined by abrasive instruments (grinding, polishing, honing, etc) as well as most of nanocoatings has the irregular surface texture, which can be described by random function. Irregular surface is expressed by a random field h(x, y) of two variables x and y which are Cartesian coordinates of a surface point, where the height of surface asperity h (x, y) has a normal probability distribution. Further in deformed volume calculation, as well as in determination of the length of the surface's contact the 3D surface roughness parameters were used in accordance with the standard ISO 25178 part 2.

The two surfaces contact model is given on Fig. 1.

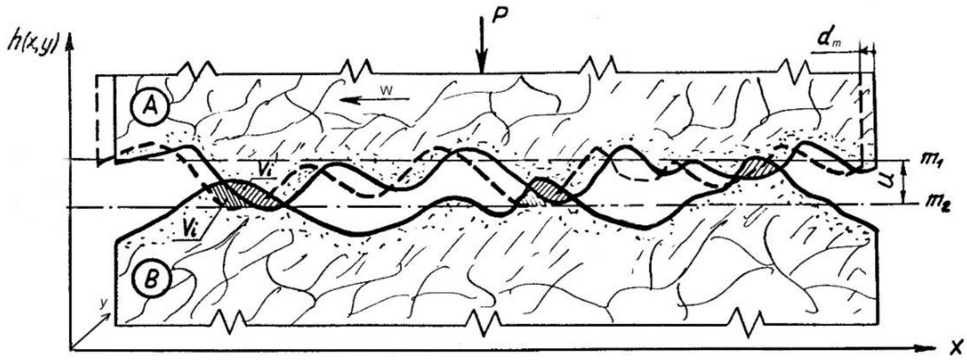


Fig.1. Two surfaces contact model: m1, m2 – mean planes of contacting surfaces; u – surfaces displacement; d_m - contact length mean value on a direction of friction for single asperity; P – load; W – speed; Vi – deformed material volumes; A, B – surface indexes.

For quantitative evaluation of the wear process the wear rate (I) can be determined for the elastic contact using following equation [7]:

$$I = \frac{h}{L} = \frac{V}{n \cdot d_m \cdot A_a}, \tag{1}$$

where: I – wear rate (surface texture material removal rate); h – texture height change, m; L – wear path length, m; V – deformed material volume of the detail, m^3; n – number of load cycles until material will be destroyed; d_m – contact length mean value on a direction of friction for single asperity, m; A_a – nominal area of contact, m^2 (Fig.2).

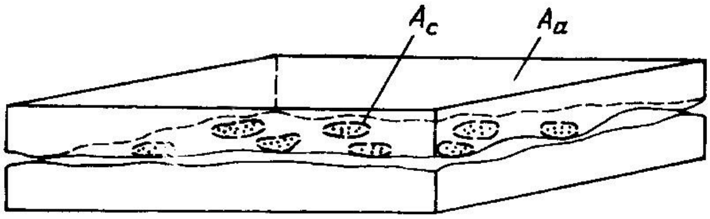


Fig.2. Contour contact area (A_c) and nominal contact area (A_a) [7].

According to Eq.1 and Fig. 1, 2 the linear wear rate can be expressed as:

$$I = \frac{Vm(u) \cdot A_c}{n \cdot d_m \cdot A_a}, \tag{2}$$

where: Vm(u) – deformed material volume of the detail, which takes into account surfaces displacement u, $mm^3 \cdot m^{-2}$.

According to [8] using normal probability distribution of texture height for calculating of each component in Eq.2 we obtain the following equation:

$$I = \left(\frac{Sa \cdot Str}{Rsm_1}\right)^{t+1} \cdot \left(\frac{4\sqrt{2\pi} \cdot f(1+\mu)}{\sigma_0 \cdot \Theta}\right)^t \cdot F(c) \cdot Smr(c), \tag{3}$$

where: Sa – arithmetic mean of the absolute height, µm; Str=Rsm1/Rsm2 – texture aspect ratio of the surface; Rsm1,Rsm2 – mean width of the roughness profile elements in two orthogonal directions, µm ; f – friction coefficient; µ – Poisson's ratio; σ_0 – ultimate tensile strength at a single load cycle, MPa; t – exponent of frictional fatigue curve [7]; F(c) – tabulated function [8], where c=u/Sq, u – surface displacement, µm, and Sq – root mean square value of the ordinate values within a sampling area, µm; Smr(c)=Ac/Aa – area material ratio of the scale limited surface; $\Theta = \frac{1-\mu^2}{E}$ – elastic constant of a material, MPa-1, where E – Young's modulus, MPa. This equation is valid for elastic contact of wear parts and it serves as the basis for proposed methodology of lifetime prediction of details.

After some simplifications we obtain following formula for engineering calculation [8]:

$$I = k_F \cdot \left(\frac{Sa \cdot Str \cdot f}{Rsm_1 \cdot \sigma_0}\right)^t \cdot \Theta^{1-t} \cdot q \cdot Smr(c), \tag{4}$$

where: *q* – load, MPa; k_F – coefficient depending on *Str* and *t*, which replaces *F(c)* within specific range of *c* values: $2 < c < 3$ [8]. Values of k_F are given in Table 1.

Table 1. Values of k_F

Str	*t* - exponent of frictional fatigue curve [6]		
	4	6	8
0,50	618×10^5	383×10^9	223×10^{13}
0,45	578	359	208
0,40	535	323	193
0,35	493	306	176
0,30	444	216	160
0,25	392	243	141
0,20	335	208	120
0,15	284	176	103
0,10	228	142	825×10^{12}
0,05	164	108	600

Analysis of Eq.3 and Eq.4 shows, that more influential on wear rate are the 3D surface roughness parameters. Graphically the influence of each parameter is given on Fig.3. During experiments the strong correlation between 3D roughness parameters *Sa* and *Str* was revealed in [8]: $Rsm \approx 35 \cdot e^{Sa}$ when $0{,}1 < Sa < 2{,}5$. That's why this influence practically decrease (dash curve on Fig.3) and more important role play mechanical and frictional properties of surface material: f, c, σ_0, Θ. Increasing of these parameters deviation the linear wear rate increases as well and in contrary. The influence of load q is not very significant in comparison with others parameters.

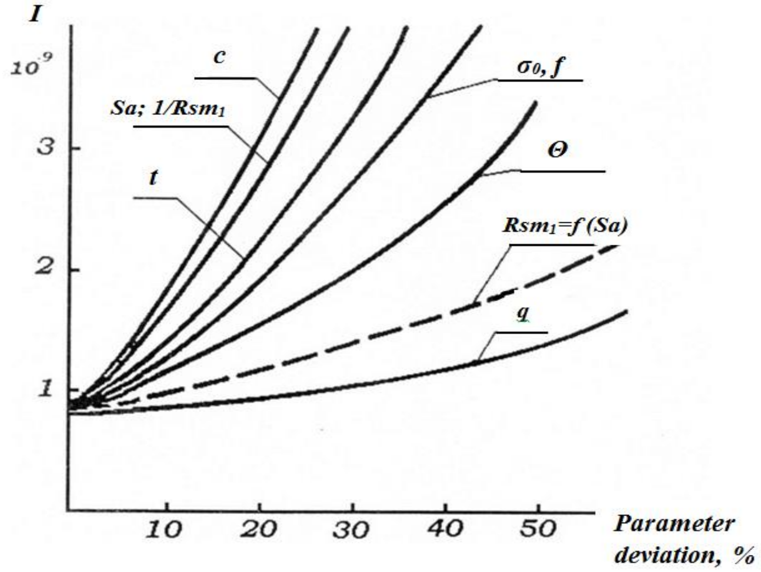


Fig.3. Influence of parameter deviation on the wear rate I for the elastic contact of wear parts.

Let's discuss more detailed the friction coefficient. Correlation between friction coefficient and surface roughness parameters exist as well [7]. Friction coefficient according to [9] can be found for one asperity as follows:

$$f = \frac{T}{N} = \frac{2A_1 \cdot \sigma_\tau}{A_2 \cdot \sigma_N}, \tag{5}$$

where: T – tangential load, N; N – normal load, N; A_1 – cross-sectional area of surface asperity, m^2; A_2 – longitudinal section area of surface asperity, m^2; σ_τ – tangential stress, Pa; σ_N – normal stress, Pa. In first approximation (taking $\sigma\tau = \sigma_N$) we obtain:

$$f = \frac{2A_1}{A_2} \tag{6}$$

Tangentially loaded area A_1 could be calculated for whole wear surface as follows [10]:

$$A_1 = L \cdot Sq \cdot \left\{ \frac{1}{\sqrt{2\pi}} e^{-1/2c^2} - c\left[1 - \Phi(c)\right] \right\}, \tag{7}$$

where: $\Phi(c) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{c} \exp\left(-\frac{t^2}{2}\right) dt$ – Laplace Function.

If it is necessary to calculate area only for one asperity the Eq.7 should be divided by the N_1 number of asperities in contact that is given by following formula:

$$N_1 = \frac{1}{Rsm_1} \cdot e^{-1/2c^2} \cdot L. \tag{8}$$

Area A_2 could be calculated for whole wear surface as follows [10]:

$$A_2 = A_a \cdot k_\eta \cdot \frac{Str}{1 + Str^2} \cdot [1 - \Phi(c)], \tag{9}$$

where: k_η - coefficient depending on *Str* [10].

Similarly to Eq.8 if it is necessary to calculate area only for one asperity the Eq.9 should be divided by the number of asperities in contact:

$$N_2 = \frac{2\pi \cdot Str}{\sqrt{2\pi} \cdot Rsm_1^2} \cdot c \cdot e^{-1/2c^2} \cdot A_a. \tag{10}$$

Taking into account relation between *Sa* and *Sq* we have combined previous formulas and obtained the following expression for friction coefficient:

$$f = \pi \cdot \left\{ \frac{1 \cdot e^{-\frac{1}{2c^2}}}{\sqrt{2\pi} \cdot [1 - \Phi(c)]} - c \right\} \cdot \frac{\left(1 + Str^2\right) \cdot Sa}{k_\eta \cdot Rsm_1}. \tag{11}$$

Eq.11 shows, that the decreasing of *Sa* or increasing of Rsm_1, which leads to more flat asperities, i.e. smoother surface, at the same time leads to decreasing of the friction coefficient *f*. k_η depends on the orientation of contact surfaces and their aspect ratios. If the texture directions for both surfaces match in the sliding direction of friction the coefficient of eccentricity is zero and $k_\eta = 1$. In another cases k_η can reach 1,4 and *f* reduces.

3. METHODOLOGY OF LIFETIME PREDICTION

For engineering calculation of lifetime of details the *I* calculation is needed. We propose to use the following methodology:

1. It is necessary to define the 3D surface roughness parameters and physical and mechanical properties of surface materials of wear parts;
2. Then the wear and fatigue characteristics have to be defined;
3. It is necessary to establish dimensional characteristics of wear parts design;
4. After analysing of function conditions of wear parts the maximal allowable value of wear h_{max} should be set;
5. Then the wear rate *I* should be calculated using Eq.4 and taking into account correlation between 3D roughness parameters *Sa* and *Str* as well as correlation between friction coefficient and surface roughness parameters Eq.11;
6. After calculating of linear wear rate *I*, it is possible to estimate the wear path *L*;
7. Knowing the wear path *L* for each specific friction pair with constant moving speed *W* the lifetime of wearing details T_l can be calculated.

4. EXPERIMENTAL PART

In experimental part authors measured 3D surface texture parameters, static sliding friction coefficient, dynamic sliding friction coefficient and slip properties for 5 different nanocoatings which had height surface asperities h(x, y) with normal probability distribution.

Experimental samples where made from identical steel plates with dimensions 28x40x4 mm and same weight (see Fig.4).

Fig.4. a) sample without coating, b) sample with coating

In order to see the difference between clean and coated samples, on sample was left as it was (Fig.4. a) but rest 4 samples were coated with different titanium-containing nanocoatings. In table 2 specific sample numbers and their coating film – forming elements are shown.

Table 2. Information about experimental samples

Sample number	Elements in coating
1-1	Uncoated
1-2	Ti, TiN
1-3	Ti, TiN
1-4	Ti, TiN, Al
1-5	Ti, TiN, Al

Firstly, 3D surface texture parameters were measured for all samples using Taylor Hobson Form Talysurf Intra 50 profilometer.

Fig.5. Taylor Hobson Form Talysurf Intra 50 profilometer.

In Fig.6 all sample 3D microtopologies are shown.

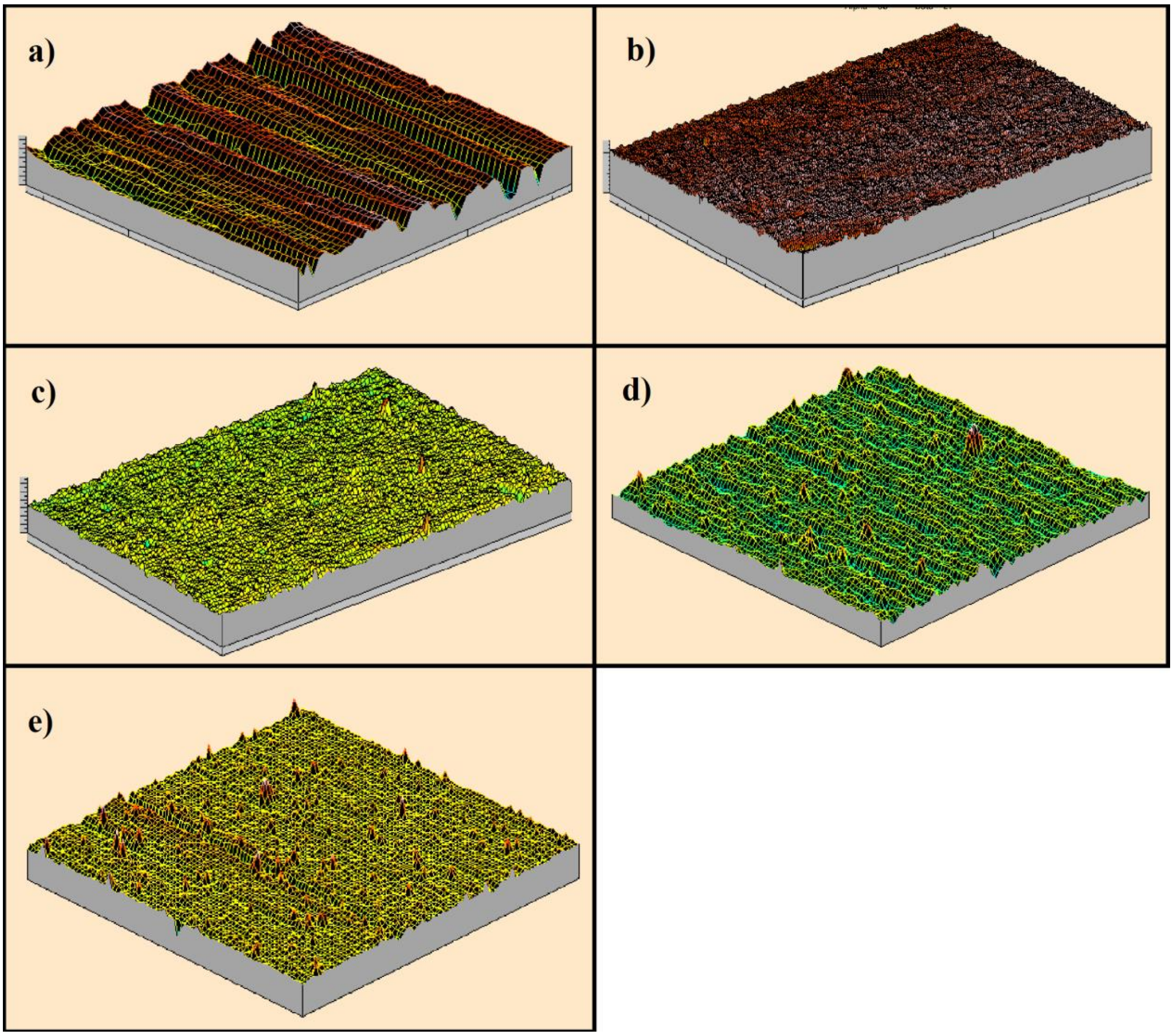


Fig.6. Experimental sample 3D microtopologies, where: a) sample 1-1, b) sample 1-2, c) sample 1-3, d) sample 1-4, e) sample 1-5.

From microtopologies calculated 3D texture parameters are following.

Table 3. Calculated 3D texture parameters

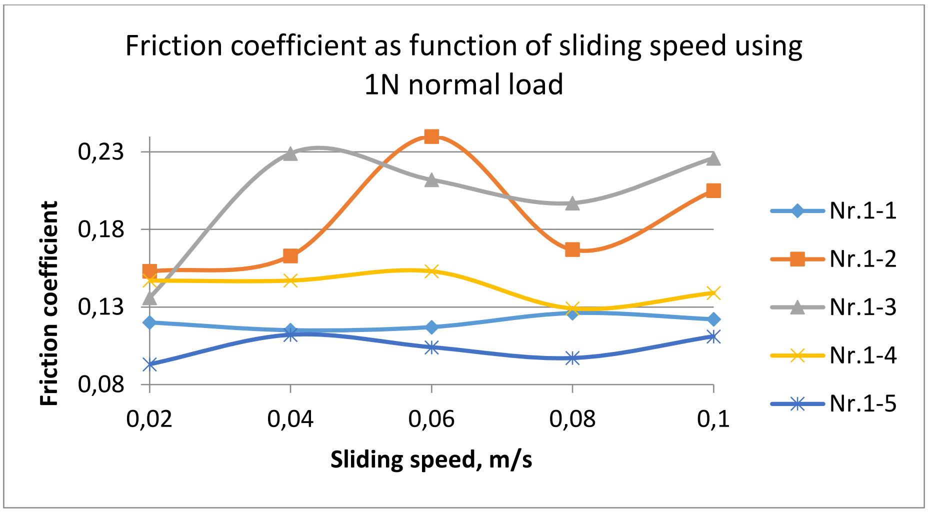
Sample	Sa (µm)	Sq (µm)	Str	Rsm_1 (mm)	Rsm_2 (mm)
1-1	0,442	0,586	0,137	0,0496	0,0890
1-2	0,0432	0,0586	0,165	0,0323	0,00875
1-3	0,0218	0,0288	0,133	0,0144	0,0130
1-4	0,0815	0,108	0,0404	0,0793	0,0861
1-5	0,103	0,187	0,0358	0,142	0,135

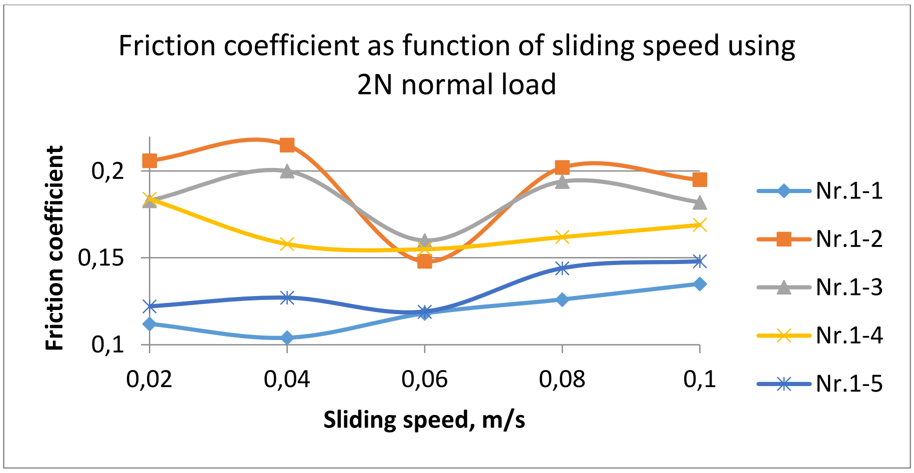
Table 3 data shoves that all coatings have smaller surface roughness than basic material on which it is sputtered.

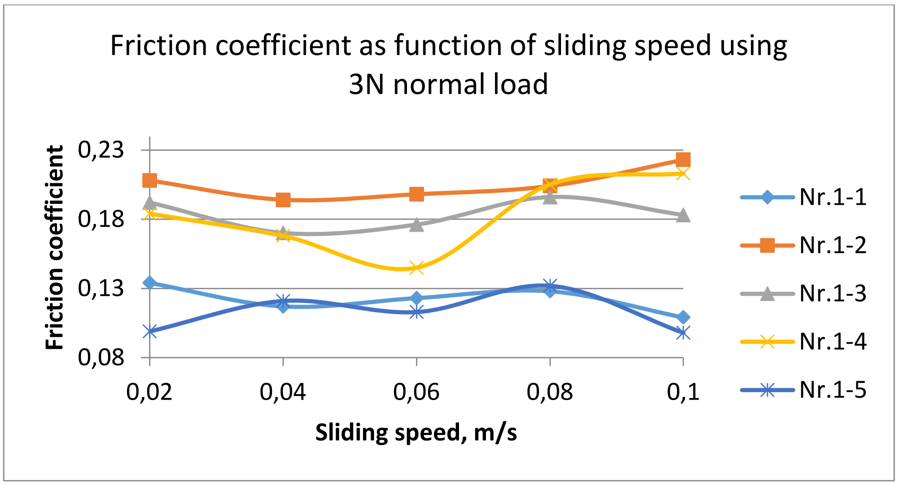
Secondly, sample dynamic sliding friction coefficients were measured using CSM Instruments pin-on-disc type tribometer CSM TRB-S-EE-0000.

Fig.7. CSM TRB-S-EE-0000 pin-on-disc type tribometer.

Using tribometer authors measured all sample dynamic friction coefficient dependence on sliding speed at 3 different normal loads – 1, 2, 3N. Acquired characteristics are as follows.







From graphs above it is possible to see that in all 3 cases samples 1-1 and 1-5 shoves lowest dynamic sliding friction coefficient and samples 1-2 and 1-3 shoves highest ones. Interesting is fact, that samples 1-2, 1-3 have smoothest surfaces, this fact allows to think that powerful adhesion component in taking part in samples sliding friction coefficient.

Finally sample static sliding friction coefficients and slip properties were investigated using self-made slip property and static friction coefficient measuring device. Principal scheme of the device is shown in Fig.8.

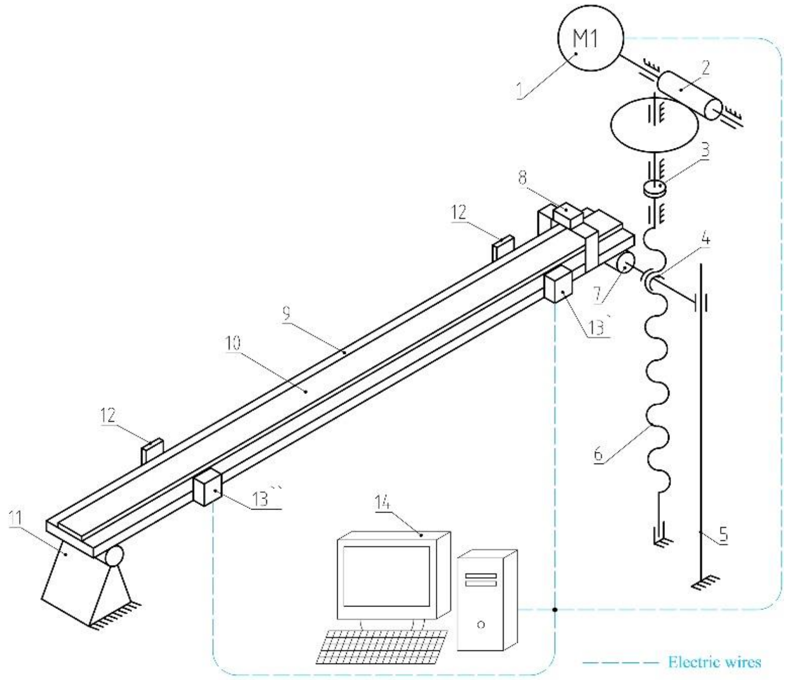


Fig.8. Slip property and static friction coefficient measuring device principal scheme, where 1) DC motor, 2) redactor, 3) clutch, 4) nut platform, 5) linear guide, 6) threaded rod, 7) roller 8) sample movement blocking device, 9) incline plane, 10) variable plates, 11) knuckle, 12) optical sensor reflector, 13) optical sensor, 14) PC for control and data analyse.

Using slip property measuring device, time, that was necessary for experimental samples to slide all the way down the inclined plane (distance between both optical sensor), was measured using optical sensors (Fig.8. 13) as movement detecting devices. As well sample static sliding friction coefficient was measured using same device – samples were located on incline plane than angle of plane was increased until sample started it`s movement.

Knowing the angle at which sample started it`s movement static friction coefficient can be calculated. In all following experiments authors used polished stainless steel plate (Fig.8. 10) as basic material for incline plane.

Static sliding friction coefficient measurements are following.

Table 4. Static sliding friction coefficient measurements

Sample / Nr.	1-1		1-2		1-3		1-4		1-5	
	Sliping angle, °	Friction coefficient	Sliping angle, °	Friction coefficient	Sliping angle, °	Friction coefficient	Sliping angle, °	Friction coefficient	Sliping angle, °	Friction coefficient
1	8,0	0,141	9,5	0,167	7,0	0,123	10,0	0,176	6,5	0,114
2	9,0	0,158	9,0	0,158	8,0	0,141	9,5	0,167	6,5	0,114
3	9,0	0,158	7,5	0,132	9,0	0,158	9,0	0,158	6,0	0,105
4	8,5	0,149	6,5	0,114	8,0	0,141	9,5	0,167	5,5	0,096
5	9,0	0,158	6,5	0,114	7,0	0,123	10,0	0,176	5,5	0,096
6	10,0	0,176	7,0	0,123	8,0	0,141	8,0	0,141	4,5	0,079
7	9,0	0,158	7,0	0,123	9,0	0,158	9,5	0,167	4,5	0,079
8	9,0	0,158	8,0	0,141	8,0	0,141	9,0	0,158	5,0	0,087
9	9,5	0,167	7,0	0,123	7,0	0,123	9,0	0,158	5,0	0,087
10	10,0	0,176	8,0	0,141	8,5	0,149	9,5	0,167	7,0	0,123
Average value	9,1	0,160	7,6	0,133	8,0	0,140	9,3	0,164	5,6	0,098

Table 4 data shows that also in this test sample 1-5 has lowest sliding friction coefficient.

In slip property measuring experiments same ambient temperature (t=21°C), inclined plane angle (α=17°) and sliding distance length (L=1,6m) was maintained during all experiment to maintain reliable results. Each sample had 500 time measurements and final result was calculated as average value from all measurements. Under such experimental settings, it was possible to compare average sliding time for all samples and thus draw conclusions about which coating shows the best slip properties.

Slip property (sliding time) measurements are following.

Table 5. Slip property (sliding time) measurements

Information about samples	Number	1-1	1-2	1-3	1-4	1-5
	Coating elements	Uncoated	Ti, TiN	Ti, TiN	Ti, TiN, Al	Ti, TiN, Al
Average sliding time, s		1,739	1,631	1,547	1,7	1,368
Time difference , s		-	0,108	0,192	0,039	0,371

According to table 5 data all 4 coated samples shows better sliding time results than uncoated sample. This allows to conclude, that titan – containing coatings improves surface sliding properties.

During experiments authors verified that self – made measuring device is very practical and reliable way of comparing different nanocoatings sliding properties.

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