Wear Calculation Model for Sliding Surfaces with Nano-Coatings

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***Abstract* –Scientists over the world develop, improve and apply different types of nano-coatings that are meant to increase the lifetime of details and to get the required exploitation characteristics. One of the essential characteristics of the sliding-friction pairs is the lifetime which is largely determined by the process of wear. The given calculation model for friction surfaces with nano-coatings is described by a separate section of the probability theory - random field theory using standardized 3D surface roughness parameters, detail's physical-mechanical characteristics, sliding surface constructive-kinematic parameters. The wear process is explained using fatigue theory approach.**

***Keywords* – wear, calculation model, surface roughness.**

I. Introduction

The wear process of surfaces (including surfaces with nano-coatings) is complex and is characterised and affected by a variety of parameters: geometry of surface peaks (roughness, buckles, form deviation, ect.), condition of physical mechanical upper layer, sliding-friction details material, wear temperature, wear conditions, etc. Due to the wear process complexity it is not possible to take into consideration all the parameters and therefore the wear calculation development in the course of time went into several directions (see Table 1.). Each direction was based on theoretical calculations taking into account assessing sets of the affecting quantities.

II. Surface Roughness Model and Initial Parameters

When studying irregular surface roughness, the random function theory method is efficient, thus the surface micro-topography can be described by a two-dimension ***random function***, i.e. random field h(x,y) with two variables x and y.

Random function is a function the value of which at each specified argument (or several arguments) value is a random size and when the random function depends on several parameters, it is called a ***random field***. The random field can be *normal*, i.e. ordinates of such field are distributed according to the normal distribution law.

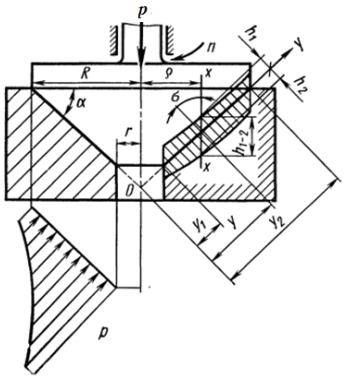
An important random function characterising value is ***correlation function*** pointing at correlation between random function points, thus the faster the correlation function wears out, the more chaotic is the random function. The correlation function depends on two variables τ_1 and τ_2, where τ_1 and τ_2 are the projections of vector τ, connecting two surface points, on the of abscissa and ordinates axis in Cartesian coordinate system.

In this case an irregular character friction surface model can be defined in the following way: *surface roughness is described by a normal uniform two variable x and y random field h(x, y), possessing ergodic properties and whose correlation function is uninterrupted and has uninterrupted derivatives.*

TABLE I

SHORT SURVEY OF HISTORICALLY DEVELOPED WEAR CALCULATION MODELS

Calculation model group according to assessing sets of affecting parameters	**Formula/calculation scheme**	**Positive/negative features**
First group - calculation model is closely connected with the application of the probability theory for the prediction of fitting's service life, calculating it mathematically. Using this approach it is possible to predict unexpected friction pair operation failures.	$P(t) = e^{-\lambda t}$ P - the fitting's non-failure probability operation; λ - the failure intensity (λ=const)	+ simplicity of the method; - parameter λ must be found previously (making experimental researches); - method not connected with the factors affecting component operation directly, i.e., component physical and mechanical properties, load, movement speed, etc.
Second group - calculation model is closely connected with the laws of classical physics. The supporter of this model R.Holms connects the wear process with interaction of the atoms of contacting surfaces and following atom separation, thus proposing to calculate the volume of worn-out material. In its turn C.D.Strong believes that during the wear process material particles separate according to the dislocation theory principles, yet E.Rabinovich links surface particle separation with surface energy phenomena.	$W = z\frac{N}{HB}$ N – load affecting components; HB – Brinell material hardness; z – probability of atom separation from the surface in case it comes into contact with an atom of another body.	- impossible regulation of wear processes on the level of engineers work.
Third group - calculation model links the wear speed γ with specific pressures p of friction pairs and relative sliding movement speed v. The representative of this approach professor Pronykov identifies two wear types – *surface* wear and *friction* fitting's wear.	$\Delta h = f(x, y)$ x and y – friction surface coordinates.	+ calculations are based on the material wear regularities and assess fitting's configuration;

Calculation model group according to assessing sets of affecting parameters	**Formula/calculation scheme**	**Positive/negative features**
Surface wear is characterised by the change of component size into the direction that is perpendicular to the friction surface Δh. In general case wear spreads on the friction surface irregularly. In case of *friction* of two fitted surfaces, both surfaces are wearing simultaneously. This leads to the changes of mutual position of the fitted surfaces. Friction pair's wear is determined by analysing changes of geometrical position of fitted components created during interaction of these components. It is crucial that these calculations are based on the material wear regularities and assess fitting's configuration, however the component wear resistance coefficients K_1 un K_2 included in the formula are determined only as a result of long lasting experiments and therefore there is no use to make wear calculations previously.	 Abrasive wear of cone-shaped fitting: $\gamma_{1-2} = \frac{Pn(K_1+K_2)}{(R-r)\cos\alpha}$ P – load affecting components; n – number of revolutions; K_1 and K_2 – component wear resistance coefficients; R, r – maximum and minimum friction surface contact radius.	- the component wear resistance coefficients K_1 un K_2 included are determined only as a result of long lasting experiments (no use to make wear calculations previously).
Fourth group - calculation model includes the friction pair's structural characteristic quantities and physical and mechanical parameters of the material of friction components, as well as geometrical parameters of component surfaces. This model takes into consideration the effect of material hardness and load size on the friction pair, characteristic quantities of definite material's flexibility, mode of component operation (load, speed, temperature), external conditions (lubrication, environment) and the constructive particularities of friction pair.	$V_e = \frac{kb\varepsilon^{\nu+1}A_c R_{max}}{(\nu+1)\alpha n}$ k – coefficient assessing the actual deformed volume; b, ν – approximation coefficients of surface relative support area; ε – relative approximation; α– coefficient characterising the stress and kinematic situation in the contact area; R_{max} – the top height of profile roughnesses; A_c – contact area surface; n – number of effects leading to material destruction.	-non-standard roughness parameters b and ν are used.
Fifth group - calculation model compared to the previous one, in addition to the above mentioned parameters, when calculating fitting's wear process, takes into consideration the standardised 3D surface roughness parameters according to ISO 25178-2:2012, when modelling the surface micro-topography with a definite part of the probability theory - random field theory and friction surfaces destruction according to the regularities of fatigue theory.	$U_n = V_\Sigma \frac{N_{cf}}{N_c}$ V_Σ - volume of all peaks separated as a result of friction; N_{cf} – actual number of cycles the surface peaks are exposed to; N_c – number of cycles leading to upper layer peak destruction.	+ takes into account standardized 3D surface roughness parameters; + takes into account constructive – kinematic parameters of sliding-friction pair; + takes into account fatigue characteristics of friction component material, material fatigue destruction parameters and mechanical characteristic quantities of material.

Since we can assume that the area has been set if its dispersion and standardised correlation function are known, the requirement to find the area dispersion leads to finding Sa (standard arithmetic deviation from the midplane) for the surface and the task $\rho(\tau_1, \tau_2)$ – to the determination of the corresponding roughness step parameter RS_{m1} (step perpendicular to the processing foot direction along midline) and RS_{m2} (step towards the processing step along the midline). Step parameters RS_{m1} and RS_{m2} allow determining the anisotropy coefficient c [5]:

$$c = \frac{E\{n_2(0)\}}{E\{n_1(0)\}} \quad (1)$$

where $n_1(0)$ and $n_2(0)$ – number of zeros in two mutually perpendicular directions of surface cuts x and y (i.e. in the longitudinal roughness and cross roughness directions of surface).

The same formula can be shown in the following way [5]:

$$c = \frac{E\{Sm_1\}}{E\{Sm_2\}} \tag{2}$$

The anisotropy coefficient c varies from 0…1. At c=1 the area is isotropy, but at c=0 maximum stretched, thus in one direction taking a straight line.

Thus we can formulate the rough surface initial parameter cluster – *according to the height, rough surface can be described using Sa, but in longitudinal direction - using roughness steps in longitudinal direction* S_{m1} *and cross direction* S_{m2}.

One of the most important parameters of wear processes is the number of contacting surfaces' peaks and it is crucial to know the mathematical expectation value E{Nγ} of rough surface peak number, which is calculated as follows[5]:

$$E\{N\gamma\} \approx \frac{\pi c E^2\{n_1(0)\}}{2\sqrt{2\pi}} \gamma e^{-\frac{\gamma^2}{2}} \tag{3}$$

where γ – relative cut height standardized by σ;
e – designation of exponent function.

The relative cut height γ can be calculated like this:

$$\gamma = \frac{u}{\sigma} \tag{4}$$

where u – cut height from average area value;
σ – surface roughness standard deviation.

III. Friction Surface Wear According to Fatigue Theory Principles

According to a series of researches it can be assumed that the wear process has the fatigue character - contacting material wearing process results in the formation and spreading of slits, which finally leads to the material particle separation.
Under the effect of cyclic loads varying stresses can exceed the limit over which the material upper layer suffers damages, arises and broadens slits (see Fig. 1.)

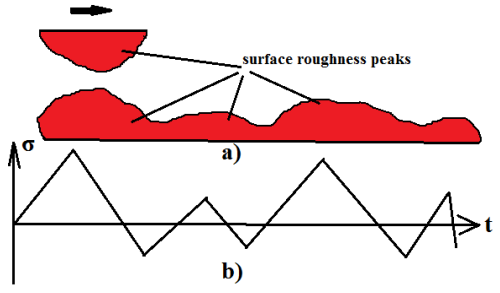


Fig.1. Irregular rough surfaces: a-peak mutual effect loading scheme; b-stress change scheme

Thus the average number of cycles for material destruction can be determined according to the following formula [1]:

$$E\{N_c\} = \frac{N_0}{5m!} t_\sigma^m \tag{5}$$

where t_σ – non-dimensional stress relation;
N_0 – number of material durability cycles at symmetric load;
m – indicator of fatigue curve equation degree.

In its turn, t_σ is being calculated using the following coherence [1]:

$$t_\sigma = \frac{\sigma_{-1}}{E\{\sigma_a\}} \tag{6}$$

where σ_{-1} – material durability limit.

The number of material destruction cycles is connected with the value of stress amplitude σ_a which can be determined as follows:

$$E\{\sigma_a\} \approx \frac{\pi\sqrt{\pi}\sigma E\{n_1(0)\}E}{K(e)} \tag{7}$$

where σ – standard deviation;
$E\{n_1(0)\}$ – mathematical expectation value of the number of zeroes (towards x direction of surface cuts);
E – material elasticity modulus;
K(e) - first order elliptical integral from contact surface eccentricity.

Since the irregular character surface roughness in the given model has been described with a normal random field h(x, y), the high peaks of this field can be described with elliptic paraboloids, the volume of whose segment is [1]:

$$V_i = \frac{\pi h_0^2}{K^{\frac{1}{2}}} \tag{8}$$

where h_0 – the height of paraboloid segment measured from the top (thickness of separated particle);
K – roughness peak Gauss' bending, which is calculated as follows:

$$E\{K^{\frac{1}{2}}\} \approx\sim E\{(k_1 k_2)^{\frac{1}{2}}\} \approx \pi^2 \sigma E\{n_1(0)\}E\{n_2(0)\}\gamma \tag{9}$$

It must be mentioned that h_0 depends on the situation of the upper layer and other physical and mechanical factors determining particle formation during friction process. Value h_0 must be evaluated based on the analyses of the upper layer condition. Making necessary alterations, the average value of the separated volume of one peak can be determined as follows:

$$E\{V\} \approx \frac{4\sigma}{\pi E^2\{(n_1(0)\}c\gamma} \tag{10}$$

Volume of all peaks separated as a result of friction are [1]:

$$E\{V_\Sigma\} \approx E\{V\}E\{N_\gamma\} \approx \frac{2\sigma}{3\pi\gamma} \quad (11)$$

Formula (11) allows determining the deformed volume per field unit. Where friction takes place in the field S_b:

$$E\{V_\Sigma\} \approx \frac{2}{3}\frac{\sigma S_b}{\pi\gamma} \quad (12)$$

Whereas the friction area is calculated in the following way:

$$S_b = L_b l_b \quad (13)$$

where L_b – total length of component friction path;
l_b – width of component friction foots.

Now formula (11) could be represented in the following way:

$$E\{V_\Sigma\} = \frac{2}{3}\frac{\sigma L_b l_b}{\pi\gamma} \quad (14)$$

IV. Wear Calculation Algorithm

The wear process usually can be characterised by three stages (see Fig.2) – running-in period, normal wear and disastrous wear, at the emergence of which the service life of a friction pair is stopped because wear affects further operation.

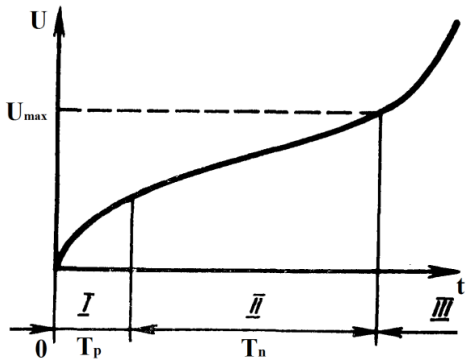


Fig.2. Dependence of wear value U on fitting operation time t;
I running-in period; II – normal wear; III – disastrous wear

According to the given calculation model, running-in period and disastrous wear period take only a small part of the whole stability time, thus maximum wear can be determined as follows:

$$U_{\max} = U_p + U_n \quad (15)$$

where U_p, U_n – the average wear value during attachment and normal operation stages.

It must be mentioned that in the given case the running-in period process parameter (U_p) is determined experimentally. This is due to the fact that during running-in period there is a big number of parameters that are highly variable and therefore it is impossible to evaluate them and include into calculations. That's why according to the offered calculation model the average wear value U_p must be determined experimentally and initial data must be determined after fitting's running-in period.

One of the ways how to define the fitting's lifetime is to characterize it with the linear wear, which can be found using the following formula [1]:

$$U_n = V_\Sigma \frac{N_{cf}}{N_c} \quad (16)$$

where N_{cf} – actual number of cycles the surface peaks are exposed to;
N_c – number of cycles leading to upper layer peak destruction.

The actual number of cycles can be calculated in the following way:

$$N_{cf} = \frac{L_b}{S^a_{m2}} \quad (17)$$

where L_b – length of friction path;
S^a_{m2} - average step of surface roughness towards friction for surface favouring wear of another surface.

Thus using formula (17) and carrying out the necessary alterations we will obtain a linear wear calculation formula [1]:

$$E\{U_n\} \approx E\{V_\Sigma\}\frac{E\{N_{cf}\}}{E\{N_c\}} = \frac{2}{3\pi}\sigma\frac{L_b}{S^a_{m2}}\frac{5m!\left(\pi\sqrt{\pi}\right)^m}{\left(3K^{1/2}(e)\right)^m}\left(\frac{E}{\sigma_{-1}}\right)^m\left(\frac{\sigma}{S_{m1}}\right)^m\frac{1}{\gamma} \quad (18)$$

where γ– relative surface deformation level.

Deformation level can be determined using basic coherences of contact theory:

$$q_{el} = \frac{k_q^{el} Ra}{RS_{m1}\theta}\cdot F_1(\gamma) \quad (19)$$

where q_{el} – pressure on contacting surfaces in elastic contact;
k_q^{el} – coefficient depending on the roughness anisotropy coefficient *c*;
F_1 - (γ) function depending on deformation level γ;
θ – constant of elastic properties of material.

Whereas pressure on the contacting surfaces:

$$q_{el} = \frac{P}{A_a} \quad (20)$$

where A_a – nominal contact area.

Elastic property constant for the material can be determined as follows:

$$\theta = \frac{1-\mu^2}{\pi E} \quad (21)$$

According to the previously mentioned formulas, the following wear calculation sequence can be proposed (see Fig.3.):

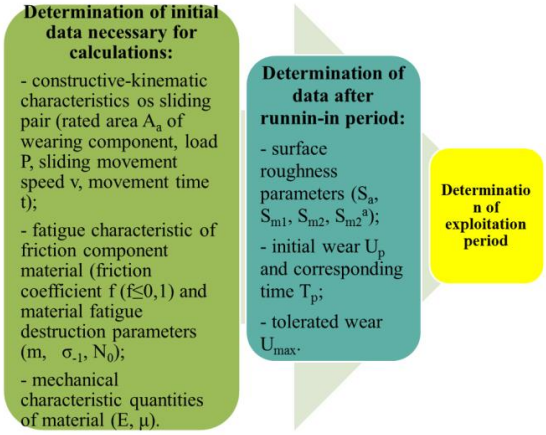


Fig.3. Wear calculation sequence of sliding-friction pairs

V. CONCLUSIONS

It must be stated that the offered calculation model and wear calculation sequence for sliding-friction pairs could be used taking into account definite wear conditions. However, in real fitting's exploitation period one could observe also other phenomena that could affect the final calculation results and due to this fact it is necessary to make further research in order to consummate and, if necessary, also supplement the above mentioned wear calculation model.

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Guntis Spriņģis, Jānis Rudzītis, Armands Leitāns, Anita Avišāne. Dilšanas aprēķina modelis slīdes pāriem ar nanopārklājumiem

Mūsdienu tehnoloģisko procesu attīstība dažādās ražošanas sfērās ļauj nodrošināt galaprodukta kvalitātes uzlabošanos. Dilšanas un ar to saistīto procesu aktualitāte vienmēr ir bijusi liela, tādējādi laika gaitā tika izstrādātas vairākas dilšanas teorijas, kuru pamatā ir dažādas zinātniskās pieejas, kuras savukārt ļauj prognozēt salāgojuma aptuveno kalpošanas laiku. Taču, veicot iepriekšminēto dilšanas aprēķina pieeju analīzi, jāsaka, ka tām pastāv arī būtiski trūkumi, kas tiešā veidā ietekmē rezultātu precizitāti un dažos gadījumos zūd jēga rēķināt salāgojuma kalpošanas laiku, jo daži aprēķinā iekļautie parametri sākotnēji ir jāatrod eksperimentāli. Piedāvātais slīdes-berzes pāru ar nanopārklājumiem dilšanas aprēķinu modelis ietver vairāku zinātņu nozaru pamatsakarības, kuras ļauj pēc iespējas pilnīgāk aprakstīt dilšanas procesa veidošanās likumsakarības un aprēķinam nepieciešamos parametrus. Dotais aprēķinu modelis berzes virsmu apraksta, izmantojot varbūtības teorijas atsevišķu sadaļu - gadījuma lauka teoriju, virsmas mikrotopogrāfijas aprakstā pielietojot standartizētos 3D virsmas raupjuma parametrus, berzes pāra detaļu fizikāli-mehāniskos raksturlielumus, salāgojuma konstruktīvi-kinemātiskos parametrus, aprakstot detaļu dilšanas procesu ar nogurumteorijas likumsakarībām.

Гунтис Спрингис, Янис Рудзитис, Армандс Лейтанс, Анита Авишане. Расчетная модель износа для скользящих пар с нанопокрытиями.

Развитие современных технологических процессов в различных сферах производства обеспечивает повышенное качество конечного продукта. Износ и связанные с ним процессы всегда были актуальными, поэтому с течением времени было разработано несколько теорий износа, которые основываются на различных научных подходах, которые, в свою очередь, позволяют приблизительно прогнозировать срок службы сопряжения. Однако проведенный анализ показывает, что у данных подходов по расчету износа существуют серьезные недостатки, которые непосредственно влияют на точность результатов, а в некоторых случаях теряется смысл рассчитывать срок службы, так как некоторые параметры, включенные в первоначальный расчет, сначала необходимо найти экспериментально. Предлагаемая модель расчета износа скользящей пары трения с нанопокрытиями включает в себя несколько сфер науки, которые позволяют более полно описать закономерности формирования процесса износа и расчет необходимых параметров. Данная модель расчета поверхности трения описывает, используя отдельный раздел теории вероятности, метод теории случайных функций, учитывая стандартизированные 3D параметры шероховатости поверхности, физико-механические характеристики пары трения, конструктивно-кинематические параметры, описывая процесс изнашивания, используя теорию усталостного разрушения.