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USING 3D NON-CONTACT PROFILOMETRY FOR EVALUATING WEAR TRACKS

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ABSTRACT

This paper presents a new method for evaluating wear tracks with the help of 3D profilometry. Using a non-contact profilometer, every wear track and its surrounding zones are recorded as a matrix, each element being given as z(x, y), z being the height of the surface in the point characterized by the position (x, y). It is described a method of identifying the limits of the wear track based on curvature radii variation, characterizing each line recorded by the profilometer. The designed pseudo code provides accurate values for the wear track area and volume.

KEYWORDS: 3D profilometry, wear track, pseudo code

1. INTRODUCTION

The functioning of triboelements made of polymeric materials requires maintaining working parameters in allowable ranges. The damages due to friction and wear processes are complex and they are the results of overlapping processes: wear, elasto-plastic deformation, expansion, shrinkage, fatigue processes, etc. [3, 8, 10, 11, 13, 15]

In many research works related to wear and especially those involving the block-on-ring tester [6], the volume of lost material is evaluated by calculation, starting from records of different parameters, such as:

- the mass loss (Δm), knowing the material density (ρ);
- the approach between the triboelements, (Z), recorded by the tribometer [3, 12];
- the width of the wear track (b), usually measured after the test ends.

The authors noticed that the mass loss is very small (tenth of miligram) as compared to the mass loss of a block made of PTFE for the same testing conditions.

Also, when calculating the linear wear of the width of the wear track , there are aspects that are not taken into account, such as the macrogeometrical deviations (the flatness deviation, the cylindricity deviation of the ring, etc.) and the divergence in positioning the triboelelements at test start or, more, their deviation in time due to functioning [1, 4, 7].

2. METHOD FOR EVALUATING THE VOLUME OF THE WEAR TRACK

When comparing the values for two wear parameters, the volume determined from the mass loss of the block and the volume calculated with the approach between the two triboelements, the authors noticed differences (see Table 1). And this is why they try to evaluate the wear by a new parameter: the volume of the wear track.

This original method is based on the literature for 3D profilometry [2, 5, 9, 14], recording the surface topography of the tested blocks with the help of a 3D profilometer. The data are included in a set of coordinates X, Y, Z of the surface topography and then this set is used for calculating the volume of the wear track using the program MatLab R2009b.

For calculating the area and the volume of the wear track taking into account the data obtained by measuring the already tested blocks, the following steps are to be done:

- eliminating the block zones that are not near the wear track (Fig. 1 presents the reconstruction of the block based on the coordinates recording);
- recognizing the wear track limits;

Calculating the area and the volume of the wear track.

a) Eliminating the block zones that are not near the wear track may be done either manually or automatically, knowing the approximate values of the wear track from a set of tests (Fig. 2).

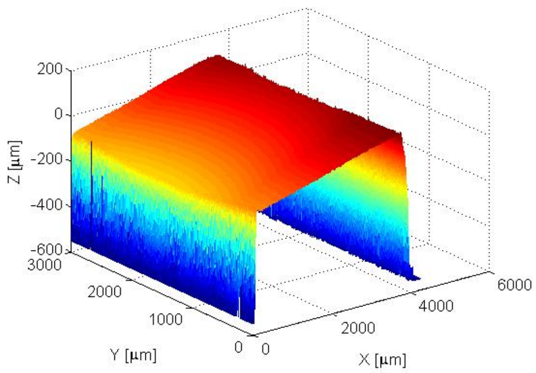

Fig. 1. *Initial data of the wear track (called here "naturale state")*

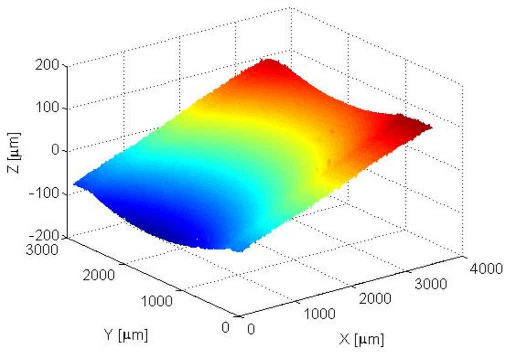

Fig. 2. *A virtual reconstruction of the data remained for evaluating the volume of the wear track*

b) For limiting the wear track, the following substeps are to be done:

b.1) Approximating each cross section of the wear track by a 10th order polynom (fig. 2.53.a)

In order to have the best approximation, the least square method is applied, that is the sum of the square values of the distances between the approximating polynom and the actual curve, has to be minimum.

$$\varphi(x) = \sum_{i=1}^{n} \left(x_{i,d} - x_{i,c}\right)^2 = min \quad (1)$$

where $x_{i,d}$ are the recorded data and $x_{i,c}$ are the values calculated by the approximation.

When fulfilling this requirement, it is possible that no actual point is included in the approximation

The polynomial regression is an approximation of a data set by a polynom as:

$$p(x) = \sum_{i=0}^{n} a_i x^{n-i} = a_0 x^n + a_1 x^{n-1} + \ldots + a_{n-1}x + a_n \quad (2)$$

where $a_0 \ldots a_n$ are coefficients.

If the data set has n elements, all the recorded data are on the approximation curve. For a smaller order of the polynom than the data number, the approximation becomes better if the polynom order is closer the data number. A polynom order greater than the data number could give considerable errors.

For a better approximation of a data set *(x, y)* with the help of a *n-th* order polynom, the function ***polyfit*** from the MatLab library, in two possible ways: p=polyfit(x,y,n) finds the coefficients of the *n-th* order polynom *p(x)*, that makes fitting the input values *p(x(i)),* in *y(i)*, and the result *p* is a line vector with *n+1* components – the polynom coefficients,

$$p(x) = p_{1x}^{n} + p_{2x}^{n-1} + \ldots + p_{nx} + p_{n+1} \quad (3)$$

[p,S]=polyfit(x,y,n) restitutes the coefficients p and a structure S; these could be used together with the function polyval for estimating the error;

b.2) The curvature calculation of the approximation polynom of each cross section

This calculation is done for extracting the shape of the wear track in the section plane. This shape could differ from a section plane to another, due to local deformations or/and local material removal (Fig. 6).

The plane curve of the wear track in a section plane could be given by a parametric representation:

$$\begin{cases} x = x(t) \\ y = y(t) \end{cases} \quad (4)$$

where *P(x(t),y(t))* is a point on the curve *C* and the slope of the tangent in the point *P* is (fig. 3):

$$k_T = tan\theta = \frac{\dot{y}(t)}{\dot{x}(t)} \Rightarrow \theta = arctan\frac{\dot{y}(t)}{\dot{x}(t)} \quad (5)$$

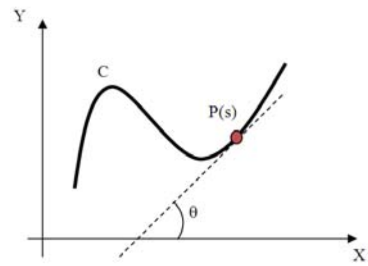

Fig. 3. *Parameter for curvature calculation*

The derivate of q related to s could be calculated and there is obtained:

$$\frac{d\theta}{ds} = \frac{d\theta}{dt}\cdot\frac{dt}{ds} = \frac{\ddot{y}(t)\dot{x}(t) - \ddot{x}(t)\dot{y}(t)}{\dot{x}(t)^2 + \dot{y}(t)^2}\cdot\frac{dt}{ds} \quad (6)$$

where:

$$ds = \sqrt{\dot{x}(t)^2 + \dot{y}(t)^2}\,dt \Rightarrow \frac{dt}{ds} = \frac{1}{\sqrt{\dot{x}(t)^2 + \dot{y}(t)^2}} \quad (7)$$

Thus, the formula for the curvature becomes:

$$k = \frac{d\theta}{ds} = \frac{\ddot{y}(t)\dot{x}(t) - \ddot{x}(t)\dot{y}(t)}{\left[\dot{x}(t)^2 + \dot{y}(t)^2\right]^{3/2}} \quad (8)$$

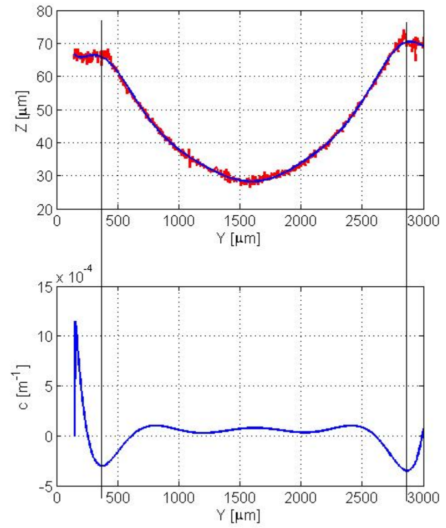

Fig. 4. *A polynomial approximation of the cross section as extracted from the wear track*

b.3) Calculation of the points of minimum curvature for a given cross section

In order to extract only the wear line in a cross section, there are determined the minimum values of the curvature in each cross section. These points limit the wear track in each cross section. Fig. 5 presents the wear track as rebuilt with the help of the original pseudo code.

The area is done as a sum of n increments each one calculated as the product between the line length and the step of the 3D investigation (in this study the step has the value of 5 μm).

For the volume of the wear track, the function *quad* from the MatLab library was used. It is a numerical method for determining the area below a curve given by a function *f(x)*.

c) Calculation of the wear track area and volume

In order to calculate the area and the volume of the wear track, the line of the wear track is approximated in each cross section with a 2nd order polynom, as given in Fig. 6.

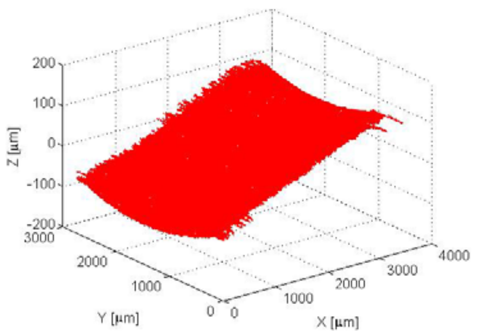

Fig. 5. *The wear track as rebuilt with the help of the original pseudo code (3D view)*

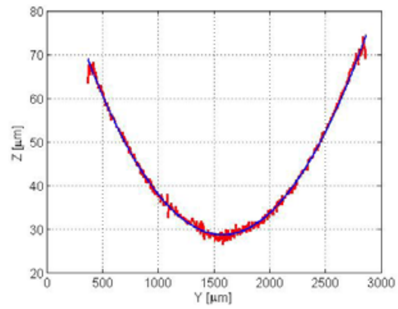

Fig. 6. *The line of the wear track in a cross section and its approximation*

The numerical integration approximates the function $\int_a^b f(x)dx$ by a squaring method (either Gauss-Lobatto or Simpson. The authors applied the Simpson method, the error being less than 0.0024631%.

The formula for Simpson method is

$$\int_a^b f(x)dx = \frac{b-a}{6}\left[f(a)+4f\left(\frac{a+b}{2}\right)+f(b)\right]+R(f) \quad (9)$$

where the rest of the formula is:

$$R(f) = -\frac{(b-a)^5}{2880} f^{(iv)}(\xi), \quad a < \xi < b. \quad (10)$$

For determining the area of each cross section of the wear track (fig. 7), the area below the 2nd order polynom is subtracted from the trapezoidal area (the trapezoid corners are given by the extreme points of the wear track).

3. SOME RESULTS AND DISCUSSION

In order to validate the designed method, the authors evaluate several wear parameters, as obtained from block-on-ring tests done in dry regime. Table 1 presents values obtained with the help of this method, but also the volume of the lost material and the geometrical volume of the wear track as calculated with the help of linear wear parameter Z.

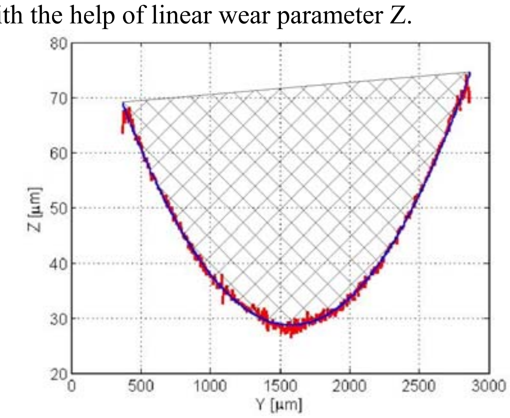

Fig. 7. *The surface for calculating the incremental volume of the wear track*

Table 1. *Values for different volumes characterizing the wear process of the blocks made of PBT+15%PTFE, after being tested at F=5N and a sliding distance L = 7500 m*

Sliding speed *[m/s]*	$V_{geometrical}$ *[mm³]*	$V_{mass\ loss}$ *[mm³]*	V_{Matlab} *[mm³]*
0.25	0.0344	0.1483	0.0781
0.50	0.0268	0.1483	0.0491
0.75	0,0232	0.1483	0.0524

The volume of the material lost by wear could be calculated as:

$$V_{mass\ loss} = \frac{\Delta m}{\rho}\ [mm^3] \qquad (11)$$

where *Δm [g]* is the mass loss being the difference between the initial mass of the block and its mass at the test end, ρ [g/mm^3] is the density of the block material, given by the specialists from ICEFS Savinesti (Romania), who manufacture the samples .

The geometrical volume is calculated as:

$$V_{\text{geometrical}} = \left(\frac{\pi \cdot R^2 \cdot \alpha}{360} - R^2 \cdot sin\frac{\alpha}{2} \cdot cos\frac{\alpha}{2} \right) \cdot l \qquad (12)$$

where *R* is the ring radius, *α* – the angle of the circle sector as determined by the approach between the two triboelements (*Z*), as recorded by the tribometer and l is the width of the tested block (Fig. 8). As the metallic ring has a very high rigidity as compared to the polymeric block, it could be assumed that Z is the depth of the wear track (also including the dilatation and the plastic deformation of the blocks the measurement is done in actual time, at the end of the test).

Figure 9 presents the wear track for the block made of PBT+15% PTFE, after testing at F=5N, v=0.5 m/s and L=7500 m. One may notice that the width of the wear track is not a rectangular one and this is one reason that introduced errors in calculating $V_{geometrical}$.

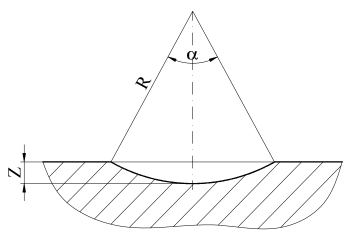

Fig. 8. *The drawing for calculating the geometrical volume of the wear track*

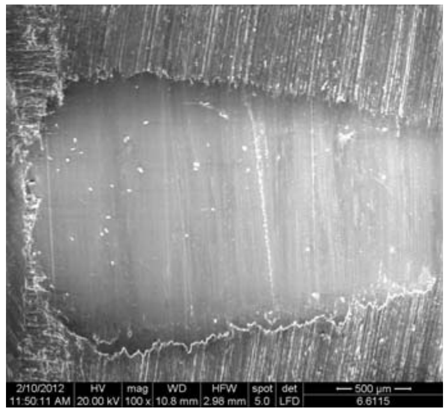

Fig. 9. *The wear track for the block made of PBT+15% PTFE, after testing at F=5N, v=0.5 m/s and L=7500 m*

4. CONCLUSIONS

The authors define the volume of the wear track, the volume of material lost by wearing process and also an approximation of the volume of the wear track depending on the approach between the two triboelement.

Modern softwares, like MathLab, allow for evaluating with high accuracy the volume of the wear tracks.

This method becomes useful when the specialist is interested in modification of the contact shape influencing the kinematics of the entire system.

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