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ANALYSIS OF DATASETS GENERATED DURING TRIBOLOGICAL TESTS AT NANOTRIBOMETER BY USING NONLINEAR REGRESSION ANALYSIS

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Abstract: *This paper studied the use of statistical methods of raw data analysis for determination of possible relationship between parameters of the tribological tests realised. We analysed raw data for the analytical relationship of penetration depth and time of contact, by using nonlinear regression method. In this way, it is possible to obtain additional quantitative parameters for characterization of contact material tested at nanotribometer. We validated proposed analytical method through tribological experiments with sandblasted samples of AlMg4.5Mn0.7 alloy and S700MC steel and the same samples coated with epoxy primer Axalta EP300R. Reciprocating sliding module was used under dry conditions, with normal load of 250 mN. Our results showed that non-linear regression analysis can be used to easily quantify the dependence of penetration depth to the duration of contact.*

Keywords: *nanotribometer, raw results, regression analysis, quantification of measurement results*

1. INTRODUCTION

In most cases, commercially available devices for testing and determining the mechanical characteristics of materials have an acquisition system from which the measurement results are collected and processed using specialized software. Measurement reports are commonly automatically prepared and provided by the device's software, usually in a locked form that cannot be changed or customised according to some specific user requirements. The good aspect of the nanotribometer acquisition system is that the measurement results can be recorded as raw data in the form of text datasets. This makes it possible to make custom analysis on the raw dataset and provide additional parameters for material characterization.

The nature of the change of many phenomena indicates their interdependent relationship, where close study of those relationships can indicate underlining governing mechanisms. Powerful tools in those studies are statistical methods, or statistics [1]. There are numerous definitions of statistics. According to Vukadinović [2], statistics can be defined as a method of quantitative research of phenomena. One of the most widely accepted definitions states that statistics is the science of collecting, organizing, presenting, analyzing, and interpreting data, which represent the input in the decision-making process [3].

Statistical research of the relationships among phenomena is carried out through multivariate analysis, which is divided into regression and correlation analysis. The subject of regression analysis is to discover the form of correlation, i.e., the form of the alignment of different phenomena. The subject of correlation analysis is to determine the strength of the quantitative alignment of the different phenomena. These two analyses complement each other [1].

In practice, it is often necessary to find a functional relationship between two or more variables. The first step in determining this relationship is collecting different values of the variables, which depend on each other. Based on the collected values, usually obtained through experiments and represented in a coordinate system, one can visually infer the curve that approximates the dependency of the mentioned variables [2].

The most commonly used approximating curves are straight line, parabola or quadratic curve, cubic parabola, n^{th}-order parabola, hyperbola, exponential curve, geometric curve, modified exponential curve, logistic curve [2].

There is a relationship between characteristics (variables) if the increase of one is followed by an increase of the other and vice versa, or if the increase of one is followed by the decrease of the other and vice versa. In the first case, the correlation is positive, and in the second, it is negative. The strength of the relationship between variables can be of different magnitudes [2]. The strongest relationship between variables is a functional one, where each value of one variable corresponds to a specific value of another. A less strong relationship, subject to greater or lesser deviations, is called a correlative or stochastic relationship.

When studying the interdependent relationships of statistical characteristics or phenomena, the form and direction of the connection are determined, as well as its strength. The set of statistical methods used to achieve this is called the theory of correlation, and the basic indicators of correlation relationships are regression equations and the correlation coefficient [2]. Regression lines are fitted to the given values of the examined variables, and the correlation coefficient shows to what extent the actual data dispersion approximates the regression line.

In this paper, statistical processing of results obtained during experimental tribological research was carried out. The dependence of penetration depth on contact time by using the non-linear regression method was analyzed.

2. METHODS

In this paper, raw measurement results from the nanotribometer were used for statistical analysis. A preliminary analysis of experimental results showing the change in penetration depth (PD) (Figure 1.a) over time reveals that the curve shape follows the trend of a classic wear curve during the initial wear phase and partially during the steady wear zone (Figure 1.b – Phase I and part of Phase II).

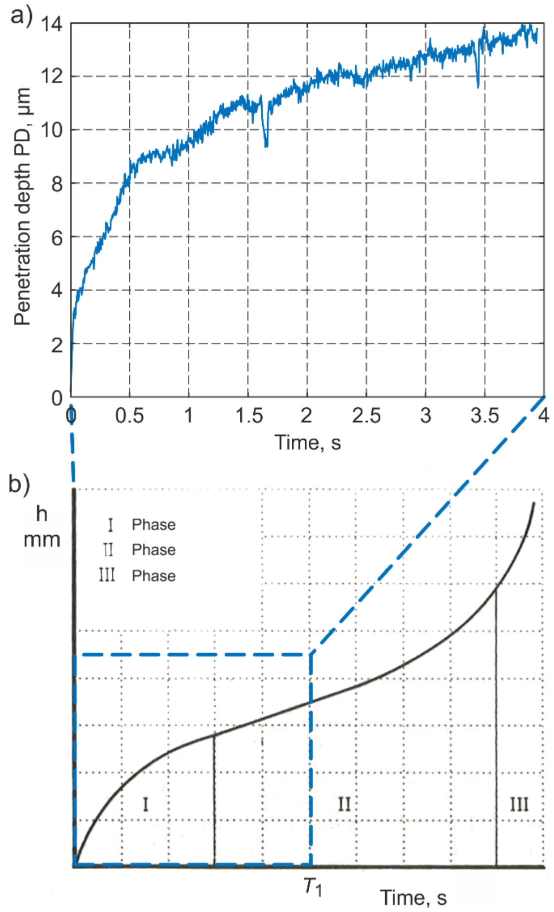

Figure 1. a) Experimental results obtained from the nanotribometer and b) theoretical shape of the wear curve

According to Ivković [4], the most suitable curves for approximating the wear curve (Figure 1.b), based on experimental results, would be of the forms given by expressions (1) and (2), where C_1, C_2, C_3, $z1$, and $z2$ are constants and exponents whose values depend on numerous factors defined by the conditions under which experimental research is conducted; h is penetration depth and T is time.

$$h = C_1 T^{z1} \begin{matrix} T = T_1 \\ T = 0 \end{matrix} \tag{1}$$

$$h = C_2 T^{z2} + C_3 \begin{matrix} T = T_k \\ T = T_1 \end{matrix} \tag{2}$$

Expression (1) is used for approximating the wear curve in the zone from T=0 to T=T_1 (zone indicated by a dashed line in Figure 1.b), and expression (2) for the zone that follows. It is important to note that the wear process represented by the curve in Figure 1.b is continuous, which means that at the transition from the first to the second phase described by expressions (1) and (2), there is a common tangent at the contact point of the two curves.

3. EXPERIMENT AND RESULTS

In this paper, experimental results obtained from the nanotribometer were considered. The nanotribometer is a precision instrument used for measuring tribological properties (like friction, wear, and lubrication) at nano- and micro-scale of loads. It is particularly useful in surface science, materials research, and the development of thin films, coatings, MEMS devices, and similar technologies.

Substrate materials used in experiments were aluminium alloy AlMg4.5Mn0.7 (EN AW 5083-H111) and steel S700MC. Two types of test samples were used: sandblasted and coated. Base material with thickness of 8 mm was cut to 100 mm in height and 100 mm in width and then sandblasted, with other group of samples sandblasted and coated afterwards. From those 100x100 mm plates, test samples with dimensions 15x15 mm were cut out using waterjet. Aluminium samples were sandblasted with white fused alumina WFA F 040, particle size: 80-110 µm under pressure of 3 bar and coated with Lankwitzer EvoCor 164-2-component epoxy primer with the thickness of the layer of 80-110 µm. Steel samples were sandblasted with steel grit WGH-40, particle size: 355-500 µm under pressure of 7 bar and coated with epoxy primer Axalta EP300R. CSM nanotribometer was used, ball-on-flat contact, with Al_2O_3 ball in sliding module. The reciprocating motion of sliding module was used, velocity of tool was 2 mm/s with amplitude of 0.5 mm. Normal load value was 250 mN.

To approximate the experimental results of PD change over time obtained from the nanotribometer, we used the recommended approximation equation given in expression (1), that can be now written in the form, given in expression (3), where a and b are unknown coefficients that need to be determined.

$$PD = aT^b \tag{3}$$

It should be noted that in equation (3), PD is expressed in *µm* and time (T) in *s*.

To determine the unknown coefficients a and b, the MATLAB and Octave function *fminsearch* was used. The operation of *fminsearch* [5] is based on the Nelder-Mead Multidimensional unconstrained nonlinear minimization algorithm [6]. It is necessary to assume the functional form of the parameter dependency being analyzed, in this case expression (3), and to provide an initial guess for the unknown coefficients a and b. By executing *fminsearch*, the sum of squared deviations between analytical and experimental values is minimized iteratively, and for a given error tolerance, the unknown coefficients a and b are determined. The *corrcoef* function [7] was used to calculate the correlation coefficient, which shows to what extent the actual data dispersion approximates the regression line, i.e., how strong the relationship is between the proposed regression curve and the experimental results.

Figures 2-5 show diagrams of PD dependence during experimental tests, as well as curves obtained by the regression analysis. Table 1 presents the values of coefficients *a* and *b* for the given experimental results, along with the correlation coefficient *R*. We denoted Al-Sand for sandblasted AlMg4.5Mn0.7 alloy; Al-Coat for coated AlMg4.5Mn0.7 alloy; St-Sand for sandblasted steel S700MC and St-Coat for coated steel S700MC.

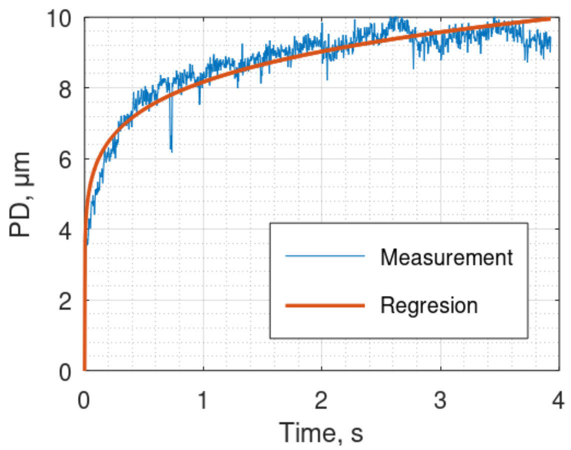

Figure 2. Contact material Al-Sand – EXP1

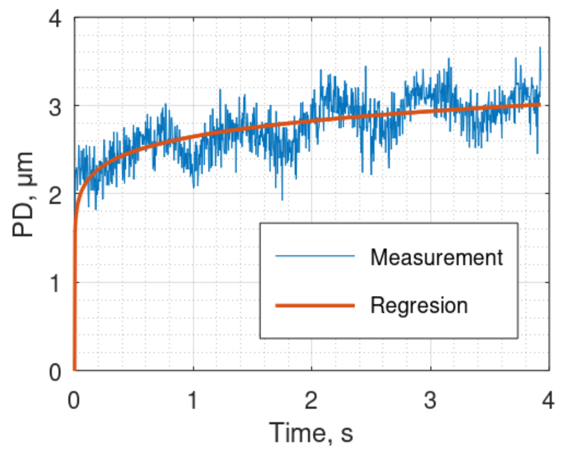

Figure 3. Contact material Al-Coat – EXP2

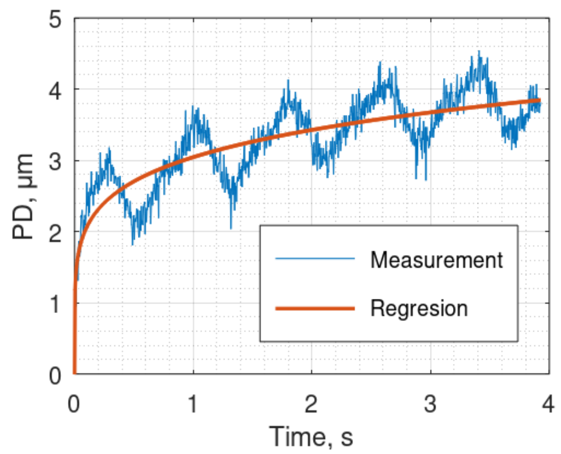

Figure 4. Contact material St-Sand – EXP3

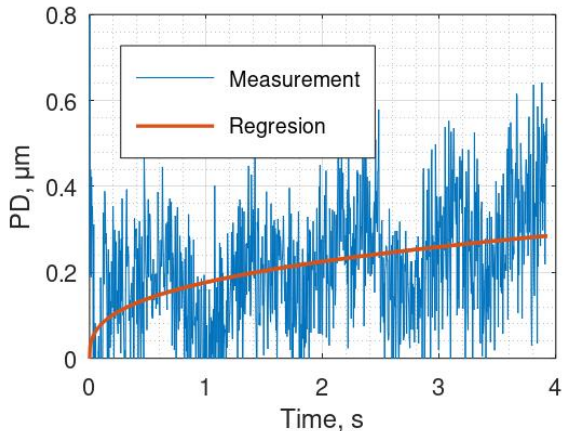

Figure 5. Contact material St-Coat – EXP4

Table 1. The experimental coefficients a and b, and correlation coefficient R

Exper. No.	Contact Material	Determined Coefficient		Corela. Coeff.,
		a	*b*	*R*
EXP1	Al-Sand	8.169	0.145	0.95
EXP2	Al-Coat	2.649	0.094	0.73
EXP3	St-Sand	3.045	0.17	0.82
EXP4	St-Coat	0.176	0.349	0.31

4. DISCUSSION

It can be concluded that the value of PD is significantly higher when the base material is AlMg4.5Mn0.7 alloy (Figure 2 and 3) compared to when the base material is steel S700MC (Figure 4 and 5), which is expected. The maximum PD value for AlMg4.5Mn0.7 alloy is ≈10 µm and ≈3 µm (for sandblasted and coated samples respectively) compared to ≈3.8 µm and ≈0.28 µm for steel S700MC (also for sandblasted and coated samples respectively). The PD value is significantly lower for coated than for sandblasted samples when considering the same base material.

The correlation coefficient is significantly high for experiments EXP1, EXP2, and EXP3 (greater than 0.7), which indicates a strong relationship between the proposed regression curve and the nature of PD change during experimental research. For experiment EXP4, the correlation coefficient is low (*R*=0.31), indicating a weak relationship between the proposed regression curve and the experimental results. The PD value in EXP4 is significantly low (below 0.5 µm) with considerable noise present, which greatly contributes to the low correlation coefficient in the case of EXP4.

The proposed regression analysis allows comparison of the experimental results through the calculated coefficients *a* and *b*. These calculated coefficients also align with the previously stated conclusions, which supports their applicability. In this way, a quantitative comparison of the experimental PD results over time can be made.

Nonlinear regression analysis can be used for fitting the model to experimental results. Analytical models with good fit are one of the foundations for developing advanced machine learning models, such as kernel-based algorithms for prediction of time series data [8]. Analysis of friction dynamics belongs to nonlinear systems, where physics-based models are very difficult for interpretation, analysis and subsequent establishment of analytical models, hence specific kernel method has been used for modelling [9]. Simple regression methods, such as in our paper can provide the initial model for further development of machine learning models that can enable easy and rapid evaluation of complex contact problems.

5. CONCLUSION

In this paper, a comparison was made of the penetration depth (PD) results depending on experiment duration on a nanotribometer with reciprocating motion. Substrate materials used in experiments were aluminium alloy AlMg4.5Mn0.7 and steel S700MC. Two types of test samples were tested: sandblasted and coated. Normal load was 250 mN. A regression analysis was carried out to represent the change in penetration depth (PD) as a function of time (T) using the proposed approximation equation. The unknown coefficients were determined, which then connect the parameters PD and T with a simple functional relationship. That makes it possible to objectively rank materials against each other according to the selected parameters. The proposed analytical method for evaluation of PD during experimental testing should be further examined on a larger series of experimental tests, given its significant potential for facilitating the quantification of research results.

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