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OPTIMISATION OF TEST PARAMETERS INFLUENCING THE DRY FRICTION OF W-DLC COATED ELEMENTS

OPTYMALIZACJA PARAMETRÓW TESTOWYCH W BADANIACH WĘZŁÓW TARCIA Z ELEMENTAMI POKRYTYMI POWŁOKĄ W-DLC

Key words:

tribology experiments, results scatter, nanotribometer, optimisation experiment, W-DLC coating

Słowa kluczowe:

testy tribologiczne, rozrzut wyników, nanotribometr, optymalizacja testu, powłoka W-DLC

Abstract

The application of thin hard coatings, such as the DLC type, acquires growing importance in the area of machine elements working under conditions of friction. Due to mechanical properties, the thin hard coatings provide the increase in the durability of coated elements, the resistance to abrasion, and protection against

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corrosion. The structure of the coatings influences the tribological properties of friction joints by lowering the motion resistance. The extension of the area of coating application is connected with the development in the field of tribological research. One of the main issues of research quality is the spread of results, especially important while considering the friction coefficient and wear resistance of friction joints with coated elements. This paper presents the application of an optimization method for the selection of test parameters for the tribological research by means of a nanotribometer. The tested friction joint consisted of steel ball rubbing against a rotating steel disc with WC/C coating under conditions of low loads. The determination of optimal test parameters for the lowest possible results spreads were conducted according to the Taguchi approach. As a result of the performed research, the differentiation of analysed test parameters in the manner of influence on results spreads was determined. The optimal test parameter values are indicated in the study. The general effects of the conducted investigation are the recommendations for tests conduction by means of nanotribometer.

INTRODUCTION

The friction coefficient of PVD coatings is often investigated using the ball-on-disc test method. The lack of a uniform and widely accepted method for testing tribological properties of thin hard coatings has caused poor repeatability and reproducibility of friction and wear results. As an example of results incomparability, obtained at various laboratories, the friction coefficient, obtained for TiN – steel friction couple, varying between 0.1 and 1.2, can be presented **[L. 1]**.

To compare and assess thin hard coatings, it was required to develop and disseminate a uniform method, carried out under laboratory conditions using a simple tribosystem **[L. 2]**.

The first step towards achieving this goal was the international research project VAMAS-TWA 1 (Versailles Advanced Materials and Standards), realised in three stages by the G-7 countries **[L. 3]**. Experiments conducted in the eighties on ceramics indicated that, to obtain good reproducibility of test results, the same test condition must be kept, especially the relative humidity, which was later been expressed in ASTM G 99-90 and DIN 50324 standards.

The second step was the international research project COST 516 Tribology. A novelty of the method was the removal of wear debris from the contact zone through the blowing of dry argon. This improved the stability of tribological characteristics and the repeatability of test results **[L. 4]**.

After these improvements, the ball-on-disc method was successfully used in many research works **[L. 5, 6]**.

For some applications, the test conditions are too severe and cause the premature intensive wear of the coating. For precise friction measurement, it is necessary to perform tests under a load below 1 N. Today, there is a lack of a uniform and widely accepted method for testing tribological properties of thin hard coatings under low loads, characterised by acceptably low scatter of results.

The objective of this study was to determine the effect of test parameters on scatter and on the minimum and maximum values of the friction coefficient and wear.

To achieve this aim, it was necessary to estimate the influence of the several factors on steel - WC/C coating friction coefficient measurement under low load conditions. However, the influence of the test conditions can be determined in an experimental way, and many experiments must be done to determine the optimal ones.

To test the effect on the friction coefficient of only 3 parameters, while each of them has only three levels of value, (with 5 repeats), it is necessary to perform 135 test runs. If we increase the number of test parameters up to 5 and the level of parameters up to 4 (with 5 repeats), it will be necessary to perform 5120 test runs. It is expensive and time consuming. In laboratory practice, it is nearly impossible. The only solution is to limit the number of test runs using a statistical optimisation method.

OPTIMISATION METHOD

To solve the problem of the selection of test parameters in the ball-on-disk method and the excessive number of the test runs, the Taguchi method was proposed **[L. 7]**. The method uses specially designed orthogonal arrays to study the entire parameter space with a finite number of experiments, saving investigation time, reducing cost, and enabling the identification of significant factors.

Originally, Taguchi's statistical methods were used to improve the quality of manufactured goods, which combine the experiment design theory and the quality loss function concept. The Taguchi method was used, inter alia, in the optimisation of technological processes, e.g. the optimisation of deposition parameters of chromium carbide CrxCy coatings **[L. 8]** and electroless Ni-P coatings **[L. 9]**.

The Taguchi method was also used for the evaluation of the effect of the test conditions on the scatter of the friction coefficient measurements **[L. 10]** and for designing experiments in ball-cratering abrasive wear testing **[L. 11, 12]**, as well as for the optimisation of test parameters in ball-on-disk tests **[L. 13]**.

TRIBOLOGICAL TESTS

The W-DLC coating was deposited on 100Cr6 steel using the PVD process by reactive sputtering.

Before the deposition, the surface of the tested discs were polished to obtain a mirror-like quality of the surface (Ra = 0.004 μm).

The WC/C (Tungsten Carbide/Carbon) coating (also denoted as a-C:H:W or W-DLC) is a DLC type representing a-C:H:Me group. This coating is composed of hard tungsten carbide particles in a softer amorphous carbon matrix. The coating consists of an elemental Cr adhesion layer adjacent to the steel substrate, followed by an intermediate transition region consisting of alternating lamellae of Cr and WC and a hydrocarbon layer doped with W. The detailed design of WC/C coating is depicted in **Figure 1**.

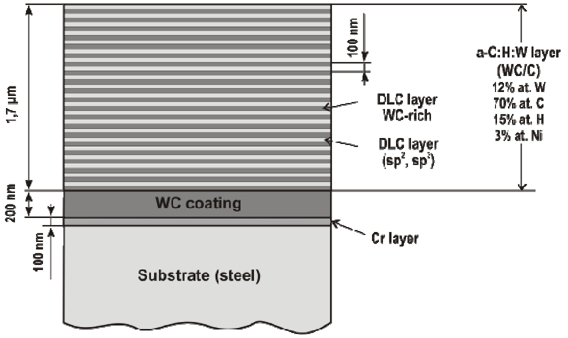


Fig. 1. Design of the WC/C coating
Rys. 1. Struktura powłoki WC/C

The tribological tests were conducted using a CSM Nanotribometer **(Fig. 2)** using a ball-on-disk tribosystem.

Fig. 2. The view of Nanotribometer used in the research
Rys. 2. Nanotribometr wykorzystany w badaniach

During the test, a steel bearing sphere is loaded onto the sample with a precisely applied force. The friction coefficient is determined during the test by measuring the deflection force on the arm.

The three courses of friction coefficient obtained consecutively and in the same conditions are presented in **Figure 3**.

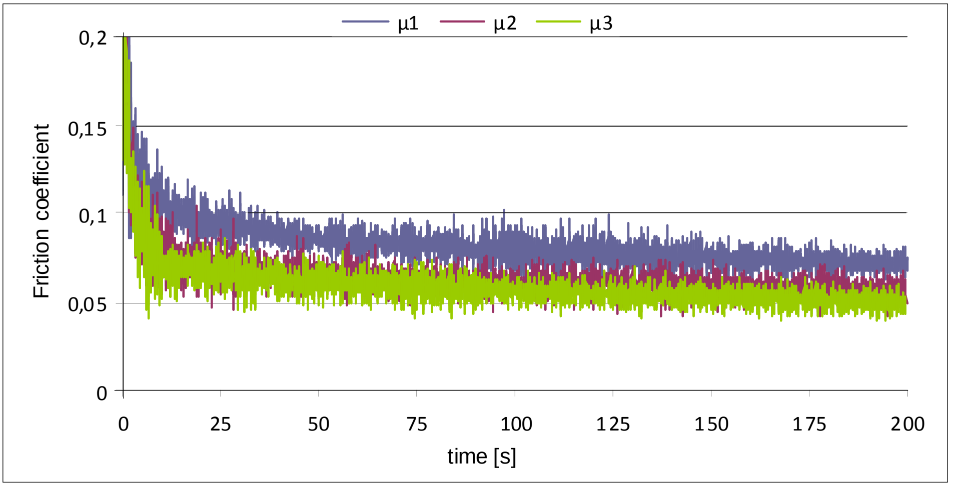


Fig. 3. The fluctuations of friction coefficient
Rys. 3. Przebiegi zmian współczynnika tarcia

The effect of 3 parameters (load, sliding velocity, wear track radius) were tested, each having three levels of value on the friction coefficient and wear. The levels of tested parameters are listed in **Table 1**.

Table 1. Levels of tested parameters
Tabela 1. Zestawienie parametrów testowych

Level	Load, mN	Sliding velocity, cm/s	Wear track radius, mm
1	10	1.0	1.0
2	50	2.5	2.5
3	100	5.0	5.0

By means of the Taguchi method, the optimal combination of the parameter values was determined with the number of experiments significantly decreased. (Nine friction experiments were designed – **Table 2**). Every experiment was repeated 3 times.

Table 2. Plan of the research
Tabela 2. Plan eksperymentu

No.	Load	Sliding velocity	Wear track radius
1	L1	V1	R1
2	L1	V2	R2
3	L1	V3	R3
4	L2	V1	R2
5	L2	V2	R3
6	L2	V3	R1
7	L3	V1	R3
8	L3	V2	R1
9	L3	V3	R2

From each test, the friction coefficient as an average value and the wear scar diameter on the steel ball were determined.

The wear of the coated discs was immeasurable. The process parameter combinations that cause the lowest and highest friction and wear for this couple were determined.

RESULTS

The results were analysed in order to identify the effect of different parameters on the tribological characteristics, namely, the friction coefficient and wear.

To determine the effect that each parameter has on the output, the value of the Eta function was calculated that characterised the signal-to-noise ratio.

Firstly, the minimum scatters of the friction coefficient and wear were analysed. The Eta values for the analysed parameters of the scatter of the friction coefficient are presented in **Fig. 4**.

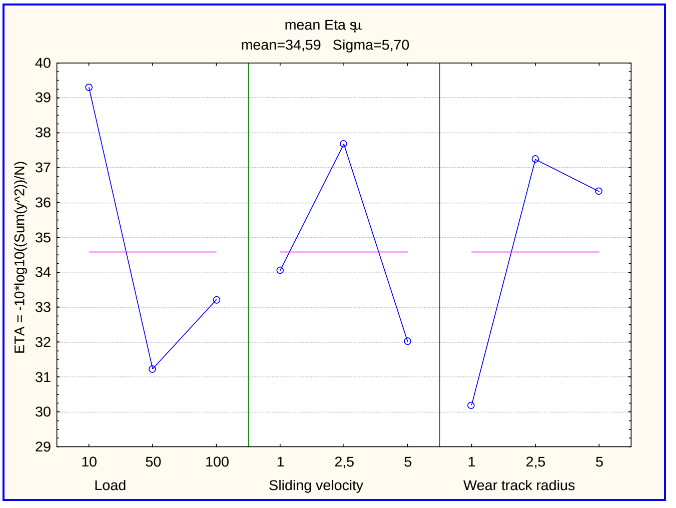


Fig. 4. The Taguchi graph for the minimum scatter of the friction coefficient
Rys. 4. Wykres Taguchiego dla minimalnych rozrzutów współczynnika tarcia

For minimising the scatter of the friction coefficient, the following values for parameters should be given:

- load – 10 mN,
- velocity – 2.5 cm/s,
- wear track radius – 2.5 mm.

The Eta values for the analysed parameters of the scatter of the friction coefficient are presented in **Figure 5**.

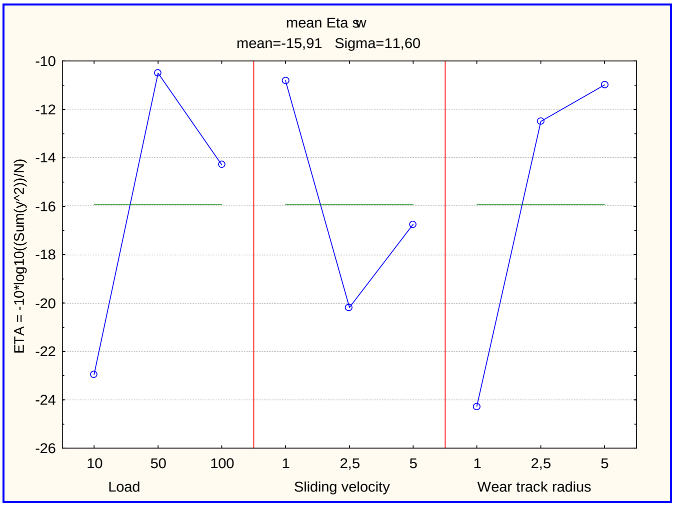


Fig. 5. The Taguchi graph for the minimum scatter of the wear
Rys. 5. Wykres Taguchiego dla minimalnych rozrzutów współczynnika tarcia

For minimising the scatter of wear, the following values for parameters should be given:
– load – 50 mN,
– velocity – 1.0 cm/s,
– wear track radius – 2.5 mm or 5 mm.

The minimum values of the friction coefficient and wear were analysed. For minimising the performance characteristics, the following definition of the Eta function were calculated for each experiment according to the equation presented below:

$$Eta_{(\min)} = -10 \cdot \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$$

where: yi – output performance,
n – number of measurement.

The Eta(min) values for the analysed parameters of friction coefficient are presented in **Figure 6**.

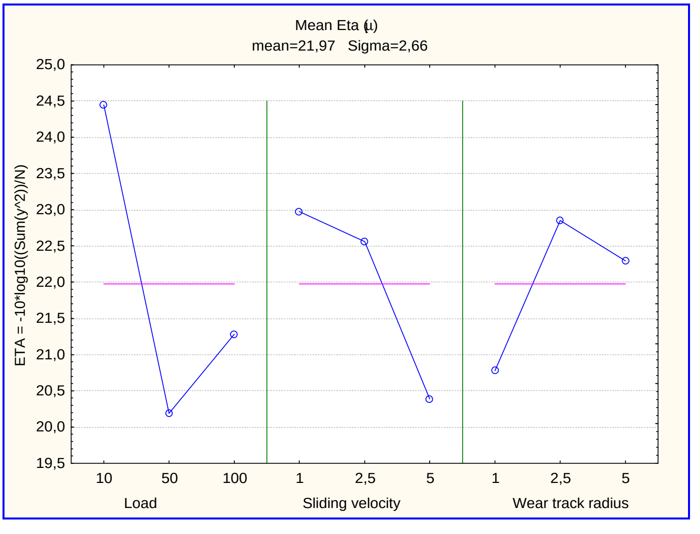


Fig. 6. The Taguchi graph for the minimum of the friction coefficient
Rys. 6. Wykres Taguchiego dla minimalnego współczynnika tarcia

For minimising the friction coefficient, the following values for parameters should be given:
– load – 10 mN,
– velocity – 1.0 cm/s,
– wear track radius – 2.5 mm.

The biggest impact on the minimum value of the coefficient of friction was from load.

The Eta(min) values for the analysed parameters of wear are presented in **Figure 7**.

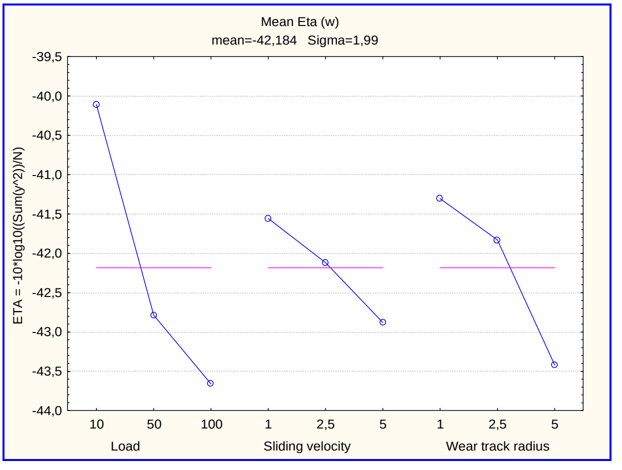


Fig. 7. The Taguchi graph for the minimum of the wear
Rys. 7. Wykres Taguchiego dla minimalnego poziomu zużycia

For minimising wear, the following values of parameters should be given:
– load – 10 mN,
– velocity – 1.0 cm/s,
– wear track radius – 1.0 mm.

In the case of wear, the biggest impact on the minimum value of wear was also from load.

The obtained research results were used to select test parameters under which the projected value of wear is minimal. For those parameters, the projected minimal wear is 106.9 µm.

The verification test was performed for selected optimal test parameters. The wear scar on the test ball is presented in the **Figure 8**.

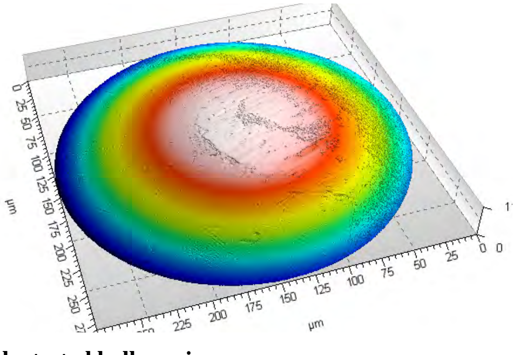
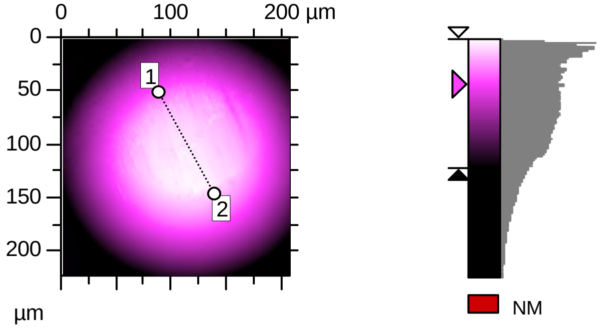


Fig. 8. Wear scar on the tested ball specimen
Rys. 8. Ślad zużycia na kulce testowej

The way of determining the wear value as a wear scar diameter is presented in **Figure 9**.



Kursor 1	Kursor 2
X = 88.40 µm	X = 138.6 µm
Y = 50.54 µm	Y = 146.4 µm
Z = 10.90 µm	Z = 12.13 µm

Odległość pozioma	108.1 µm
Różnica wysokości	1.224 µm
Odległość wektorowa	108.1 µm

Fig. 9. Image of the wear scar and the diameter measurement
Rys. 9. Schemat pomiaru średniej średnicy śladu zużycia

As the result of the verification test run, the wear value z = 108.1 µm was obtained. The optimization of test parameters in respect to obtaining the lowest wear was verified.

CONCLUSION

The tribological experiments with the use of a ball-on-disk CSM Nanotribometer were conducted. To solve the problem of the effect of the test parameters on the minimum and maximum values of friction and wear, the Taguchi method was used.

Using the Taguchi method, the number of experiments was significantly decreased. The test parameters to obtain the minimum scatter of results were proposed. The minimum and maximum value of the friction coefficient and wear value, and the impacts of the test parameters on these values, were also considered.

Load has the biggest impact on the minimum value of the coefficient of friction and wear. The other parameters have a significantly lower level of impact on the friction coefficient's minimum value.

Load and sliding velocity have the greatest impact on the maximum value of the friction coefficient.

The Taguchi method turns out to be a very effective for the evaluation of the effect of numerous parameters on friction and wear.

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Streszczenie

Twarde, cienkie powłoki przeciwzużyciowe, w tym DLC, są coraz częściej stosowane na elementy maszyn. Powłoki tego rodzaju charakteryzują się dobrymi właściwościami mechanicznymi, zapewniają bardzo dobrą odporność na utlenianie i mają bardzo dobre właściwości tribologiczne. Dalszy rozwój w tym obszarze wymaga zastosowania odpowiednich metod badawczych, zapewniających możliwie wysoką jakość wyznaczanych wartości wskaźników charakteryzujących właściwości tribologiczne. Istotny problem stanowią rozrzuty wyników badań tribologicznych, szczególnie współczynnika tarcia oraz zużycia.

W artykule przedstawiono zastosowanie metody optymalizacji parametrów procesu tarcia w badaniach właściwości tribologicznych prowadzonych z wykorzystaniem nanotribometru. Badaniom poddano skojarzenie materiałowe powłoka W-DLC-stal. Wyznaczenie parametrów procesu optymalnych ze względu na rozrzut wyników przeprowadzono metodą optymalizacji zgodną z podejściem Taguchiego. W wyniku przeprowadzonych badań wykazano zróżnicowanie wpływu analizowanych parametrów na rozrzuty wyników pomiaru oraz wyznaczono wartości optymalne parametrów. Rezultatem przeprowadzonych analiz są zalecenia prowadzenia pomiarów wartości wskaźników tribologicznych z zastosowaniem nanotribometru.