SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
2 (162) 2010

MAGDALENA TRZOS*, DEMÓFILO MALDONADO CORTÉS**

The effect of the test condition on the scatter of the friction coefficient measurements

Key words

Friction testing methods, unlubricated friction, friction coefficient, measurement reproducibility.

Słowa kluczowe

Metody badań tarcia, tarcie bezsmarowe, współczynnik tarcia, powtarzalność pomiaru.

Summary

The test results of friction coefficient measurement scatter are presented and evaluated. The friction coefficients of three different materials of friction couples under dry conditions were investigated. Ball-on-ring tests with both a vertical and a horizontal position of the sample axis and ball-on-disk tests for each friction couple were carried out in order to compare the tribotester influence on the scatter of results. The tribological experiment encompassed trials of different values of the friction process parameters: humidity, load, and velocity. The influences of process parameters on the scatter of results were analysed to assess the scatter level as a dependence on both tribotester and friction process parameters. Based on test results, the dependence between friction coefficient measurement scatter and load was revealed. The ratio of scatter to the measured friction coefficient was investigated. This error is dependent on scatter and also on the value of the friction coefficient; therefore, its value can change if the friction coefficient changes, e.g. along with humidity changes that were experimentally illustrated. As a result of the research, the conditions of the friction process, both of the low and high levels of error ratio, were predicted. The prediction was verified in the additional experiments.

* Institute for Sustainable Technologies – National Research Institute, ul. Pułaskiego 6/10, 26-600 Radom, Poland (e-mail:magdatc@poczta.fm), phone: (48)361-42-41.
** University of Monterrey (UDEM), Mechanical Engineering Faculty, San Pedro Garza Garcia, Mexico.

1. Introduction

The key influence of the friction processes on the efficiency, reliability, and durability of produced and maintained machines and devices, on the one hand, and the lack of an uniform theory that explains the phenomenon in friction contacts on the other hand, make the experimental results the main source of information on the tribological properties of the object. Because of the multitude of theories relating to particular tribological problems, an array of experimental methods in tribology is observed. As the consequences of diverse research methods, the increasing number of tribotesters assigned to cause the specific tribological situation is developed. The analysis of friction and wear research results show the great differences of achieved results that characterise the same properties of investigated tribological objects and also the significant differences of result scatter are observed. The problem can be illustrated by the data presented in Santner's publication [1] who has collected friction coefficient values of steel – TiN couple that were achieved as the research results in a few dozen significant tribological centres in many parts of the world.

Since the analysis revealed the poor reproducibility of tribological experimental results, some of the international initiatives that aim to address the problem have been taken into consideration. The *Versailles Program on Advanced Materials and Standards VAMAS* was of great importance among them. However, the situation still remains unsatisfactory, mainly because tribological properties are not a feature of an individual material but of the friction couple materials and significantly dependent on friction contact configuration and friction process parameters.

Analysis in the scope of the VAMAS project [1, 2] have showed that reproducibility of ball-on-disk tests that depend on tribo-couple materials was quite good for pairs steel/steel and steel/coated disc but are really poor for coated ball/coated disk. Specific tribological behaviour may be different for different material pairs, and different for the material pair with or without electrical current [3]. The sample preparation is also of great importance and can influence friction data [4]. Wear particles and their exact behaviours in the contact area can affect friction in a stochastic and hence unpredictable way. The research on the influence of asperities on the instabilities of the sliding friction coefficient indicated that the extent of turbulent fluctuation of the friction coefficient could be reduced through increasing the nominal area [5]. Tribological research by Suzuki [6] indicated that the friction coefficient values depend on friction contact configuration; ball-on-disk tests gave a much higher coefficient of friction then roll/slide test. The results of the effects of load on the reproducibility of ball-on-disc test in the investigation of tin hard-coating indicated that friction behaviour characteristics of TiN sliding against aluminium surfaces is reproducible at different loads as long as the wear is confined within the TiN coating [7]. Investigation of tribological properties of boron carbide coating against steel [8] revealed that a deviation less than 15% of the mean value was observed for the friction coefficient in a steady state that was obtained under medium and high humidity; whereas, the friction coefficient at low humidity was unstable.

The scatter of test results of the lubricated friction process can be caused by chemical effects. The chemistry of lubricant base stocks and additives do affect the fatigue life level and the scatter of fatigue life data. Furthermore, lubricant chemistry effects can vary with stress and slip (conditions controlled in the gear roller tests), and tests for lubricant chemistry effects should be conducted in conditions of importance to the application [9].

The fatigue durability scatter for different materials of friction contact and different lubricants was analysed in the research of friction contact fatigue durability predictions [10].

The objective of study, presented in this article, was to estimate the influence of the several factors, primarily, the type of tribotesters, humidity, load, and velocity influence on the scatter of friction coefficient values. The Taguchi method, which enables the reduction of the number of experiments, was applied to determine the suitable testing parameters in order to obtain a minimum of result scatter of the determined friction coefficient.

The Taguchi method, which combine the experiment design theory and the quality loss function concept have been widely utilised in engineering analysis. The Taguchi method [11] uses specially designed orthogonal arrays to study the entire parameter space with a finite number of experiments, saving experimental time, reducing cost, and enabling the identification of significant factors quickly. This method, among other things, succeeded to optimise the multiple tribological performance characteristics of Electroless Ni–P coatings [12] and was applied [13] to explore how the different parameters, such as drill shape and friction angle, friction contact area ratio, feed rate, and drilling speed would affect the response parameter.

2. Experiment description

The friction coefficient tests were conducted in the Institute for Sustainable Technologies – National Research Institute with the use of professional tribotester T-10 of ball-on-ring and T-11 of ball-on-disk friction couple [14]. Dry friction processes were carried out. The tribotesters, T-10 and T-11, were designed for the investigation of the basic tribological properties of materials. They both enable the measurement of the couple friction coefficient and the investigation of surface wear intensity during a friction process. They enable result registration every second. Specifically, the T-10 tribotester is designed for the estimation of tribological properties of materials for machine elements working in a sliding condition, especially in the case of thin coatings. With the use of the T-10 tribotester, the resistance to wear and the friction coefficient of any materials working in slip friction contact can be precisely investigated in relation to their dependence on slip velocity, surface stress, and other factors. This tribotester is of two types: the vertical – T-10V with vertical friction contact and load configuration, and the horizontal – T10H with horizontal friction contact and load configuration (Fig. 1).

T10H T10V T11V

Fig. 1. Position of friction contact in T10 and T11 tribotesters
Rys. 1. Ustawienie węzła tarcia w testerach T10 i T11

Similarly, the T-11 tribotester is designed for the estimation of the tribological properties especially for the machine element materials used in sliding conditions. With the use of this tribotester, the friction coefficient and wear resistance of any friction couple materials working in sliding motion and their dependence on sliding velocity, surface stress, the type of gas in the testing chamber and others factors can be estimated. The T-11 tribotester is mounted with a vertical position of the friction couple and load. It was marked in this study by T-11V.

In the scope of the investigations presented in this article, the comparison of the friction coefficient measurements with the use of different but professional tribotesters is presented.

Three different friction contact materials were investigated in experiments of different process parameters, namely: load, velocity, and humidity. The scatter of the friction coefficient was studied, and the degree of the influence of couple materials and process parameters on scatter were analysed. The friction coefficient μ and friction coefficient scatter act as dependent variables.

The research encompassed combinations of factors, each of three levels, as shown in Tab. 1.

Tab. 1. Process parameters and theirs levels
Tab. 1. Parametry procesu oraz ich wartości

Levels	Process parameters			
	Couple's materials (M)	Humidity (H) [%]	Load (P) [N]	Speed (v) [m/s]
1	steel* disc –steel* ball (S/S)	35	5	0.1
2	steel* disc –ceramic** ball (S/C)	50	10	0.2
3	coated*** disc –ceramic** ball (P/C)	80	15	0.3

*AISI 52100, ** Al2O3, ***CrN

The same friction processes with the same combinations of factor values were repeated on different tribotesters: (T-10H, T-10V, and T11-V), and the friction distance for one process was constant and equalled 1000 m. The friction force was registered every one second during the process.

Taking under consideration the above assumptions, the large numbers of experimental investigations have to be carried out, namely, 243 experiments that need a lot of time and at significant costs. To solve this problem, the settings of friction process parameters were determined by using the Taguchi experiment design method.

In accordance with the Taguchi optimisation method, nine friction experiments were designed and, an L9, an orthogonal array was constructed, which had nine rows corresponding to the number of tests, as shown in Table 2. Each trial (process) presented in Tab. 2 recurred five-times for each of the three tribotesters.

The average scatter of measurements in experimental results is also included in Tab. 2.

Tab. 2. Values of process parameters and scatter of test results for individual tribotesters
Tab. 2. Wartości parametrów procesu oraz rozrzutu wyników badań dla poszczególnych tribotesterów

Trial no.	Process parameters				Measurements' average scatter for tribotester		
	M	H [%]	P[N]	v[m/s]	T10H	T10V	T11V
1	S/S	35	5	0.1	0.069	0.133	0.126
2	S/S	50	10	0.2	0.170	0.029	0.052
3	S/S	80	15	0.3	0.084	0.018	0.133
4	S/C	35	10	0.3	0.092	0.04	0.099
5	S/C	50	15	0.1	0.102	0.035	0.031
6	S/C	80	5	0.2	0.155	0.079	0.082
7	P/C	35	15	0.2	0.038	0.121	0.111
8	P/C	50	5	0.3	0.142	0.085	0.195
9	P/C	80	10	0.1	0.115	0.032	0.163

Average scatter and average friction coefficients based on five measurements were calculated. The scatter was calculated as the average value of the differences between each of five measurements.

The samples were properly prepared with the use of an ultra vibration-cleaning machine for cleaning with a benzene solvent.

3. Results and discussion

The results of the analysis of the tribological experiments indicate certain differences among the values of the measured friction coefficients as recorded on different tribological test devices, even though the same condition of friction processes were present. However, the achieved results proved that the differences were small with the exception of Trial No. 8, using the T-11 tribotester. Analysis of the process and experimental results (Fig. 2) indicate that the differences in measurements on different tribotesters did not depend on the materials of friction contact and process parameters. One of the smallest differences was observed for Trial Number 3 (contact material – steel –steel). The largest difference was observed in Trial Number 8, if the friction coefficient value measured on the T-11V tribotester is compared with the results achieved on the T-10V and on T-10H tribotesters. In that case, the differences of average value were above 0.25, while in the other cases, were less than 0.1.

The next analysis concerned the estimation of the influence of individual variables, namely: friction couple materials and process parameters on the scatter of the friction coefficient. The average values of scatter were calculated independently for each variable for individual tribotesters.

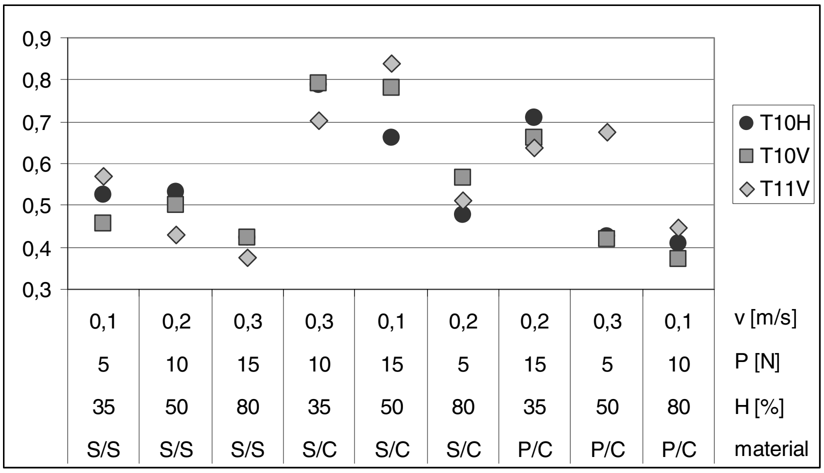

Fig. 2. Average values of the friction coefficient as the result of measurements on different tribological devices and different process parameters
Rys. 2. Wartości średnie współczynników tarcia zmierzonych z użyciem poszczególnych tribotesterów przy różnych wartościach parametrów procesu

The conducted research confirmed the influence of tribotester on the scatter of friction coefficients (Fig. 3). Actually, the smallest scatter was observed in the ball-on-ring investigation on the T-10V tribotester with the vertical position of the sample's axis of rotation. That scatter was even above threefold smaller in comparison with others. According to the research results (Fig. 3), the materials of the friction couple have an influence on the results scatter achieved on different tribological devices. The similar scatter on different tribotesters was observed for the friction coefficient of steel-ceramic couple and the differences were below 0.07, while for other materials, they were about twofold higher.

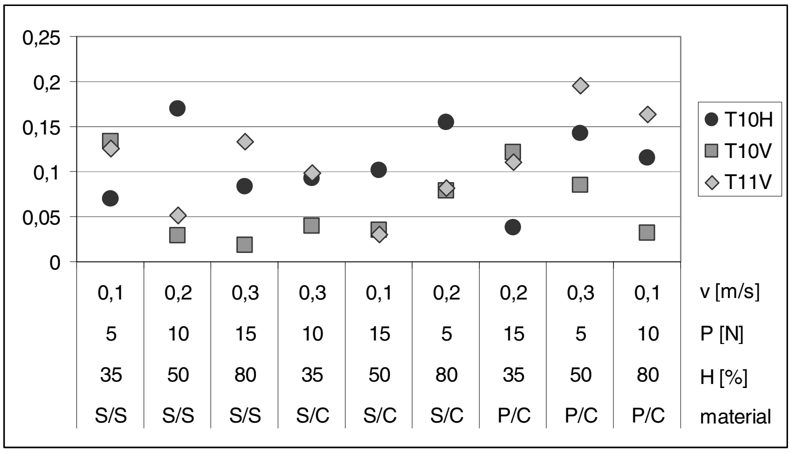

Fig. 3. Average scatters of friction coefficients on different devices and process parameters
Rys. 3. Wartości średnie rozrzutów współczynników tarcia wyznaczonych z użyciem poszczególnych tribotesterów przy różnych wartościach parametrów procesu

However, it should be pointed that, beside the absolute value of scatter in the reproducibility analysis, the scatter should be linked to the value of the friction coefficient. Therefore, additional analysis of this type was carried out to estimate the scatter influence on the error of friction coefficient measurements. To measure that influence, the coefficient b_μ was established as the ratio of average values of scatter to the average values of the friction coefficient:

$$b_\mu = r/\mu$$

Where, r is the average value of scatter (calculated as the average value of differences between each of five measurements), μ- average value of friction coefficient.

The analysis of error share, caused by scatter, in the calculated average value of friction coefficients revealed the influence of both the test devices and process parameters. As with the absolute value of scatter, the smallest b_μ coefficient was observed on the T-10V tribotester. The average value of b_μ for that tester was 12%, while for each of the other two, it was above 20%.

In order to estimate the influence of the considered, in the scope of research, parameters on share of scatter in the calculated average value of friction coefficients, the calculations were done for the b_μ average value for individual variables: speed, humidity, load, and the friction couple materials. The calculation results are presented in Figs. 4, 5, and 6.

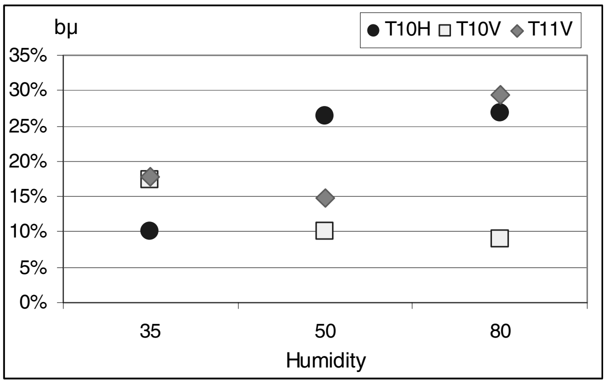

Fig. 4. Values of b_{μ} coefficient for different humidities [%] and different tribotesters
Rys. 4. Wartości współczynnika bμ przy różnych wartościach wilgotności dla poszczególnych tribotesterów

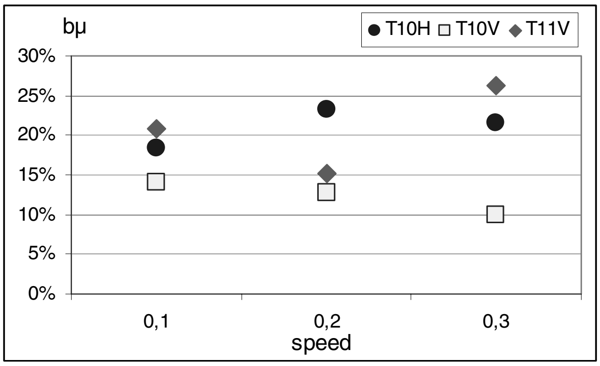

Fig. 5. Values of b_{μ} coefficient for different speeds [m/s] and different tribotesters
Rys. 5. Wartości współczynnika bμ przy różnych wartościach prędkości dla poszczególnych tribotesterów

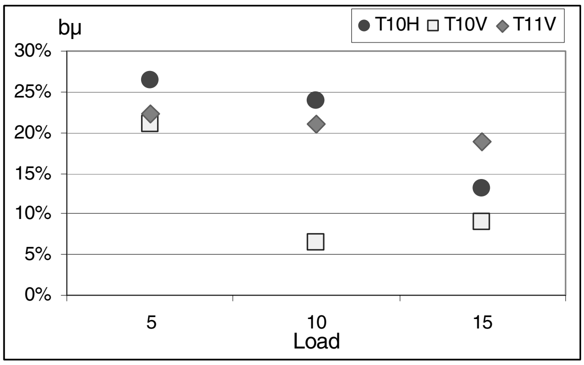

Fig. 6. Values of bμ coefficient for different loads [N] and different tribotesters
Rys. 6. Wartości współczynnika bμ przy różnych wartościach obciążenia dla poszczególnych tribotesterów

The similarities of load influence on the b_μ coefficient were noticed for all tribological devices, namely, the decrease of the coefficient while the load increases. That tendency is particularly well illustrated in Fig. 7, where load dependence on result scatter for individual friction couple materials is presented.

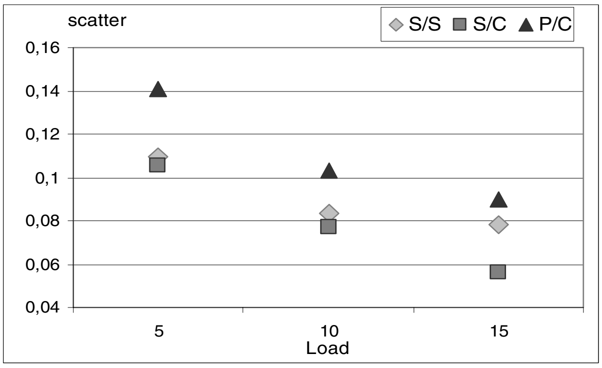

Fig. 7. Friction coefficient scatters for the different materials of friction couple and different loads [N]
Rys. 7. Rozrzut pomiarów współczynnika tarcia dla różnych materiałów pary tarcia i różnych obciążeń

As can be seen (Fig. 5), velocity has a low influence on result scatter. In case of T-10V tribotester, for which the smallest scatter is observed, along with an increase in humidity, is a decrease in the test result scatter. However, the increase of the ratio scatter to friction coefficient in case of the T-10H and T-11V tribotesters (Fig. 4), while the 50% and 80% values of humidity are considered, resulted from the change in the friction character and the decrease of friction coefficient values. This is well illustrated in Fig. 8 and 9 by the examples of changes of the friction coefficient and result scatter on T-11V and T-10H in the dependence of humidity.

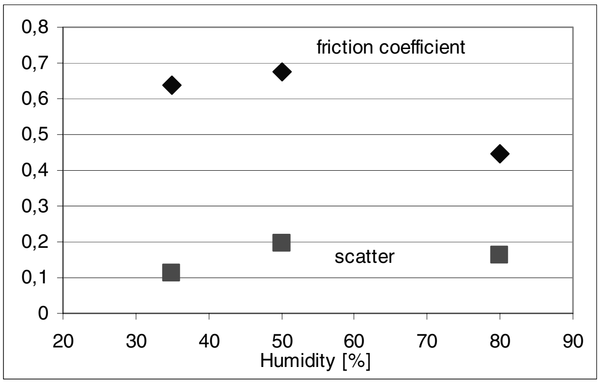

Fig. 8. The average values and average scatter of the friction coefficient of P/C materials measured on T-11V
Rys. 8. Średnia wartość i średni rozrzut współczynnika tarcia skojarzenia materiałowego P/C zmierzonego na tribotesterze T-11V

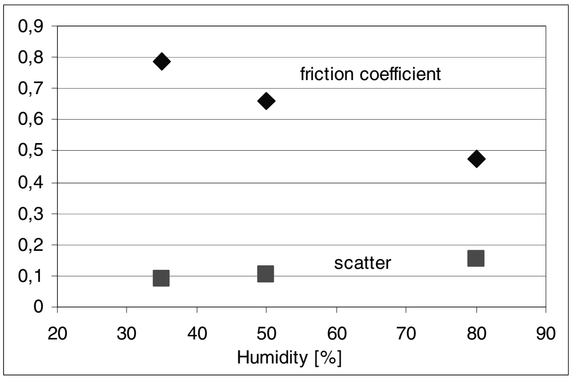

Fig. 9. The average values and average scatter of friction coefficient of S/C materials measured on T-10 H
Rys. 9. Średnia wartość i średni rozrzut współczynnika tarcia skojarzenia materiałowego S/C zmierzonego na tribotesterze T-10 H

In all analysed cases, we did not notice a scatter dependence on humidity; however, humidity influences the friction coefficient value and consequently the b_μ coefficient.

The particular analysis of experimental results revealed that measurement scatter of the friction coefficients of investigated materials, with the use of three tribotesters, does not depend on humidity and velocity but on load.

In order to verify the observed, on the basis of experimental results, influence of the noticed parameters on the scatter of friction coefficient, two additional experiments were conducted: one with a low predicted level of scatter and another with a high predicted level of scatter. The values of parameters for each of the verification processes are presented in Tab. 3. The b_μ values achieved as the result of verification are also presented.

Tab. 3. Friction process parameters and b_μ values achieved as the result of verification
Tab. 3. Wartości parametrów procesu tarcia i bμ uzyskane w rezultacie badań weryfikacyjnych

Predicted scatter level	Process parameters					scatter share in measured friction coefficient b_μ [%]
	Tribotester	Couple's materials	Humidity [%]	Load [N]	Speed [m/s]	
low	T10V	steel–ceramic (S/C)	50	10	0.1	7
high	T11V	coated steel –ceramic (P/C)	50	5	0.3	31

Each of the verification processes was repeated three times, and the average values of the friction coefficient and scatter were calculated. The verification results proved both high (0.16) and low (0.07) friction coefficient scatter predicted based on previous analysis. Therefore, the possibility of scatter level prediction and, as consequence of prediction, the planning research with low scatter, for example, increasing the number of experiment repetitions while predicted scatter level is high was indicated.

4. Conclusions

On the basis of friction coefficient measurements conducted on different testers for different materials and friction process parameters, the main conclusion are summarised as follows:

(1) The differences in result reproducibility on different tribotesters were revealed. A ball-on-ring tester with a vertical position of rotation axis (T-10V) had the smallest value of scatter and scatter share in the friction coefficient value compared with other investigated testers.

(2) Despite the differences of the reproducibility of results, the average values of friction coefficient measured with the use of different testers were comparable, while the materials of couple and friction parameters were the same.

(3) The friction coefficient scatter decreases with increasing load. That regularity was proved for all analysed tribotesters in the scope of friction parameters and friction couple materials investigated.

(4) From the test results, the humidity influence on scatter was not noticed. However, the change of the friction coefficient with the change of humidity may cause a change of scatter share in the friction coefficient measured value.

(5) The test results analysis did not prove scatter dependence on velocity.

(6) The identified relation of result scatter and factors that were analysed enabled the estimation of friction coefficient scatter level depending on friction process parameters. This information can support the research planning in a way that enables a possible small share of scatter in the measured values of the friction coefficient.

Acknowledgements: This research was sponsored by Polish Ministry of Science and Higher Education, under grant Number 2865/B/T02/2009/37.

References

[1] E. Santner, Comparison of wear and friction measurements of TiN coatings, Tribologia 1/95 (1995) 7–29.

[2] H. Czichos, S. Becker, J. Lexow, International multilaboratory sliding wear tests with ceramics and steel,. Wear 135 (1989) 171–191.

[3] H. Zhao, G.C. Barber, J. Liu, Friction and wear in high speed sliding with and without electrical current, Wear 249 (2001) 409–414.

[4] K.C. Ludema, Friction, wear, and lubrication – a textbook in tribology, Boca Raton (Florida), CRC Press (1996).

[5] H. Zhai, Z. Huang, Instabilities of sliding friction governed by asperity interference mechanisms, Wear 257 (2004) 414–422.
[6] M. Suzuki, Comparison of tribological characteristics of sputtered MoS_2 films coated with different apparatus, Wear 218 (1998) 110–118.
[7] M.Z. Huq, J. P. Celis, Reproducibility of friction and wear results in ball-on-disc unidirectional sliding tests of TiN-alumina pairings, Wear 212 (1997) 151–159.
[8] P.D. Cuong, H.-S Ahn, E.S. Yoon, K.H. Shin, Effects of relative humidity on tribological properties of boron carbide coating against steel,. Surface & Coatings Technology 201 (2006) 4230–4235.
[9] W. Castro, D.E. Weller, K. Cheenkachorn, J.M. Perez, The effect of chemical structure of base fluids on antiwear effectiveness of additives, Tribology International 38, (2005) 321–326.
[10] M. Trzos, W. Piekoszewski, R. Ruta, The number of research courses influence on the estimation of friction contact fatigue durability scatter of lubricated rolling contacts. Tribologia 230, (2010) 163–175.
[11] W.H. Yang, Y.S. Tarng, Design optimization of cutting parameters for turning operations based on the Taguchi method, J Mater Process Technol 84, (1998) 122–129.
[12] P. Sahoo, S.K. Pal, Tribological Performance Optimization of Electroless Ni–P Coatings Using the Taguchi Method and Grey Relational Analysis, Tribol Lett 28, (2007) 191–201.
[13] H.M. Chow, S.M. Lee, L.D. Yang, Machining characteristic of friction drilling on AISI 304 stainless steel, Journal of materials processing technology 207, (2008) 180–186.
[14] D. Maldonado, Influence of test parameters on the coefficient of friction, Tribologia 222, (2008) 83–92.

Manuscript received by Editorial Board, January 15th 2010

Wpływ parametrów procesu na rozrzut pomiarów współczynnika tarcia

S t r e s z c z e n i e

Zaprezentowano rezultaty badań rozrzutów współczynnika tarcia. Badania przeprowadzono dla trzech różnych skojarzeń materiałowych w warunkach tarcia suchego. Przeprowadzono testy z użyciem tribotestera z węzłem kula–pierścień zarówno z poziomą, jak i pionową pozycją osi węzła oraz tribotestera z pionową pozycją ustawienia osi węzła kula–tarcza w celu porównania wpływu urządzenia badawczego na rozrzut wyników badań. Eksperyment tribologiczny obejmował różne wartości parametrów procesów tarcia: wilgotności, obciążenia oraz prędkości. Przeanalizowano wpływ parametrów procesu na rozrzut wyników badań, aby ocenić poziom rozrzutu w zależności zarówno od urządzenia, jak i parametrów procesu. Na bazie uzyskanych rezultatów wykazano zależność rozrzutu wyników pomiaru współczynnika tarcia od obciążenia. Analizie poddano również współczynnik szacujący błąd wynikający z udziału rozrzutu w wyznaczonej wartości współczynnika tarcia. Udział tego błędu zależy zarówno od rozrzutu wyników, jak również od wartości samego współczynnika tarcia, dlatego też jego wartość może się zmieniać wraz ze zmianą wartości współczynnika tarcia, np. na skutek zmiany wilgotności, co zostało eksperymentalnie wykazane i zilustrowane. W wyniku przeprowadzonych badań i analizy wyników wyznaczono warunki pomiarów współczynnika tarcia zarówno o niskim, jak i wysokim poziomie rozrzutu wyników pomiaru. Przeprowadzone eksperymenty weryfikacyjne potwierdziły prognozowane poziomu rozrzutów.