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Friction

COEFFICIENT OF DYNAMIC BEHAVIOUR AS PARAMETER FOR TiN COATING CONDITION MONITORING

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ABSTRACT

Destruction process of the TiN coating, obtained by the PVD procedure, is considered in this paper. Investigations were performed on tribometers with ‘pin-on-disc’ contact geometry and with dry/lubricated contact surfaces. For quantification of dynamic processes in the contact zone, the coefficient of dynamic behaviour that represents the ratio of dynamic and static components of the friction force were used. Research results show that it is possible to use coefficient of dynamic behaviour as a parameter for monitoring the processes stability in the contact zone. This parameter can be used for TiN coatings condition monitoring and identification of early stages of coating destruction.

Keywords: TiN coating, coating destruction, coating condition monitoring, coefficient of dynamic behaviour.

AIMS AND BACKGROUND

Constant trend in development of new materials has been focused on improving of their mechanical (stiffness, strength, toughness and fatigue resistance) and tribological characteristics (friction coefficient, wear resistance, etc.). Significant progress has been achieved after the initial phase of PVD coating development in the 1960’s and beginning of their implementation in the 1970’s. TiN coatings have good resistance to high temperature, wear and corrosion and they can be found in applications such as cutting tools, bearing spindles, sliding bearing, ring springs, gasket elements, valves and many other mechanical components[1–5].

One of the first commercially presented PVD coatings was TiN coating. Since its appearance until today, this coating occupies attention of industry and

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researchers. This is primarily related to the tribological, economic and environmental aspects of its implementation[6–10]. Investigation of phenomena related to the application of TiN coating is still very actual and is defined by its good tribological characteristics and universality as it covers approximately 90% of coating market[11]. The tribological characteristic of low-friction PVD coatings strongly depends on coating topography and morphology. As result a different type of coating surface post treatments has been developed such as polishing, microblasting[12], etc.

TiN coating condition can be directly identified by microscopic methods, usually by using scanning electron microscope (SEM), or indirectly through identification of changes in nature of friction coefficient, electrical resistance of contacts[13], etc. Practical application of microscopic methods for investigation of realistic elements embedded in common technical systems is unacceptable because of prices and need for frequent system disassemble, while monitoring of friction coefficient changes is usually insufficiently sensitive.

One of still very actual topics in researches related to the application of TiN coatings is connected to reliable on-line identification of coating destruction process. This destruction implicates danger for function and integrity of tribomechanical system element with TiN coating. Response to these questions should draw attention to the development of sensors for identification of condition and available resources of tribomechanical system elements with TiN coating, which is the subject of this paper.

CRITERIA FOR EVALUATION OF DYNAMIC PROCESESS IN THE CONTACT ZONE

Widely used way to display the results of tribological investigation is intended to provide the dependence of the friction coefficient μ on the contact time, sliding distance, the number of revolutions, etc. Choice of how the friction coefficient μ will be shown depends on the type of contact, testing methodologies, etc. In this way, dependence of friction coefficient as a function of time (in the time domain) is presented.

On a large number of diagrams of this type, dynamic behaviour changing of friction coefficient during the experiment can be found. It is possible to identify wear stages (running-in stage, steady-state stage and catastrophic wear stage) through zones with low or large deviation of friction coefficient from mean value.

It is clear that the friction coefficient has a dynamic nature. In order to visualise the stability of friction coefficient a scatter value, $\Delta\mu$, is used[12]:

$$\Delta\mu = \frac{\mu_{max} - \mu_{min}}{2} \tag{1}$$

where $\Delta\mu_{max}$ and $\Delta\mu_{min}$ are maximum and minimum friction coefficient within specified sliding interval, respectively.

All of this implicates to very significant dynamic processes in the contact zone. Idealised form of the dynamic nature of the friction coefficient is shown in Fig. 1. In real conditions of performing the experiment on the contact pair 'pin-on-disk' changes in dynamics of the friction coefficient mainly comes from the fact that the plane of the moving disk is not ideally perpendicular to the rotation axis. Practical recording of friction force contains also some other influences, where some of them have characteristics of the stochastic process (vibrations that come from the driving motor, friction variator, setup noise measurements, etc.).

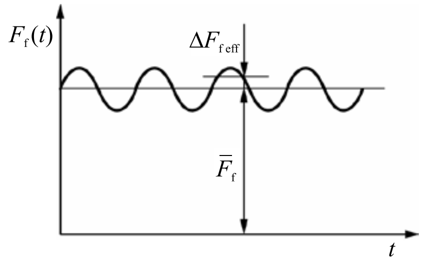

Fig. 1. Idealised form of the friction force

In order to identify changes in the friction coefficient dynamics, coefficient of dynamic behaviour (KDB) K_d, is introduced in this paper. This coefficient represents the ratio of effective value of the friction force dynamic component $\Delta F_{f\,eff}$ to the average value of the friction force $\bar{F}_f$ (Fig. 1):

$$K_d = \frac{\Delta F_{f\,eff}}{\bar{F}_f}. \tag{2}$$

Apart from the KDB, it was necessary to determine the structure of the friction force dynamic component. Due to that it was necessary to transform the friction force dynamic component from the time domain into the frequency domain. This was done by the Fourier integral that reads:

$$F(j\omega) = \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t}\, \mathrm{d}t \tag{3}$$

and which transforms the time function of friction coefficient $f(t)$ into a continuous spectrum in the frequency domain. The function $F(j\omega)$ is called the amplitude spectral density.

For analysis of the friction force dynamic component content, we used the energy spectral density ($S(\omega)$) (power spectrum) which is defined as a product of the complex conjugate values $F(j\omega)$ and $F^*(j\omega)$:

$$S(\omega) = F(j\omega)\,F^*(j\omega) = \left|F(j\omega)\right|^2. \tag{4}$$

EXPERIMENTAL

SETUP AND TESTING PROGRAM

Geometry of tribological contact configuration ('pin-on-disk') as well as the components of the experimental and measurement setup are shown in Fig. 2. The friction force and normal load signal, which are obtained from the strain gauges based dynamometer, is being transferred into the A/D converter card within PC. In the PC, with support of specialised software, the processing and storage of the recorded signals, that carry information about the friction force, are done. Post-processing of the recorded data is done with MATLAB software package.

Prepared testing program predicted measurement of friction forces (continuously over the certain time interval), i.e. their dynamic components as a function of materials of the contact elements, sliding speed, normal load, and present quantity of lubricant in the contact zone.

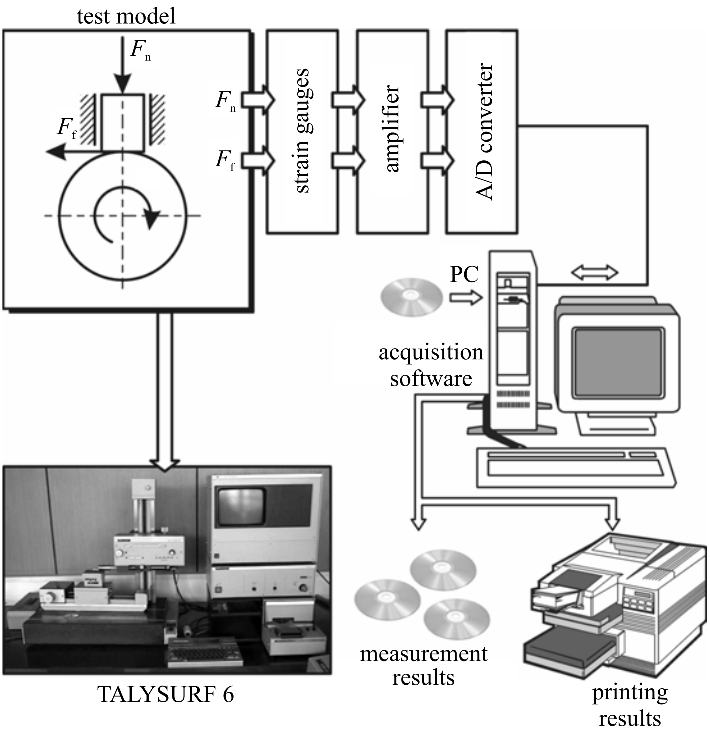

Fig. 2. Schematic of the experimental setup

TESTING CONDITIONS

Contact pair consists of pin and disc (contact 'pin-on-disc') as it is shown in Fig. 2. Contact between them was along a line of 9 mm length (theoretical idealisation).

– Rotating disc was made of carbon steel (0.35% C) for hardening with subsequent tempering, of 180 HB. The contact surface was roughly ground, and then polished. The disc diameter was 35 mm, and width 10 mm.

– Pin was made of carbon steel (0.35% C) for hardening with subsequent tempering, then coated with a very thin TiN coating (1 μm) applied by the arc procedure. The contact surface was ground prior to coating deposition.

– Lubrication multigrade oil was SAE-15 W/40 (MIL-L-46 152 B).

– Sliding speed was $V_{sl} = 1$ m/s.

– Normal load was $F_n = 5$ daN.

In the initial phase (0) of contact realisation, the friction process is defined by materials of the contact elements $(TiN/STEEL)_0$, contact surfaces topography (amplitude distribution, bearing ratio, roughness, etc.), lubrication conditions, normal load, and the sliding speed.

After the initial phase of the friction process the 'tribological balance' (TB) is being established, i.e. $(TiN/STEEL)_{TB}$. This is primarily manifested through change of topography of this contact surface, and change of the friction force nature.

In the later phase, the destruction process (D) of TiN coating begins, thus contact is partially realised between the TiN and steel, e.g. TiN/STEEL, and partially between steel and steel – STEEL/STEEL.

The mentioned process can be represented in the following way:

$$(\text{TiN/STEEL})_0 \Rightarrow (\text{TiN/STEEL})_{TB} \Rightarrow (\text{TiN and STEEL/STEEL})_D$$

Tests were made with lubricated surfaces and dry surfaces. During experiments the following parameters were considered: friction coefficient, KDF, friction coefficient power spectrum, surface roughness and surface topography. The aim was to determine which of these parameters may identify the beginning of TiN coating destruction.

RESULTS AND DISCUSION

Lubricated surfaces. Changing of friction coefficient and KDB is shown in Figs 3 and 4. There is a great match in the trends of changed these two parameters. On these diagrams 4 phases can be noted.

The first phase ($t \approx 0-10$ min) is characterised by a slight decreasing in the value of considered parameters. In the second phase a slight increase of these parameters can be noticed (friction coefficient between $t \approx 10$–30 min, and the

KDB in the period from $t \approx 10–20$ min). After that followed the third phase in which a slight decline in both considered parameters (coefficient of friction between $t \approx 30–50$ min, and the KDB in the period from $t \approx 30–50$ min) has been observed. TiN coating destruction occurred in the period $t > 50$ min, which is identified with rapid growth of the friction coefficient and the KDB-a (Figs 3 and 4).

Prominent instability of friction process starts with initial destruction of the TiN coating ($t > 50$ min). Under these conditions, dynamic load intensifies in the contact zone, and that in turn leads to more intensive coating destruction.

Change of dynamic processes in the contact zone, in the phases of stable and unstable friction process (the TiN coating destruction process) is best illustrated by the power spectrum of the friction coefficient (Figs 5–7). The dynamic component of friction coefficient is decomposed to the sum of harmonic component by power spectrum. On these diagrams clearly is observed a dominant characteristic

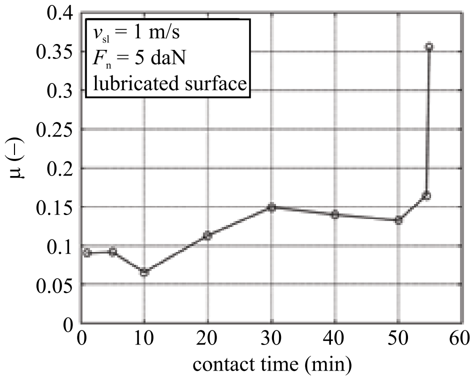

Fig. 3. Friction coefficient as a function of contact duration time

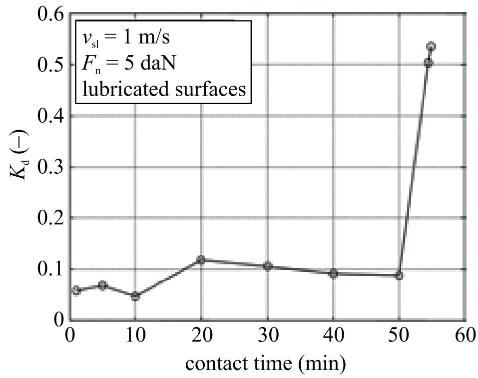

Fig. 4. KDB as a function of contact duration time

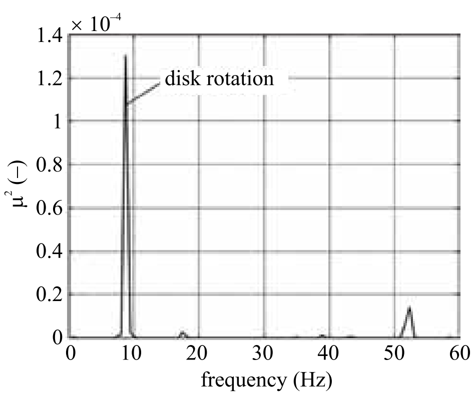

Fig. 5. Power spectrum of the friction coefficient after the contact duration time of 20 min

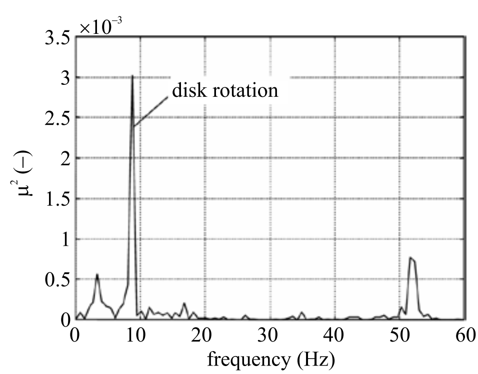

Fig. 6. Power spectrum of the friction coefficient after the contact duration time of 54 min and 20 s

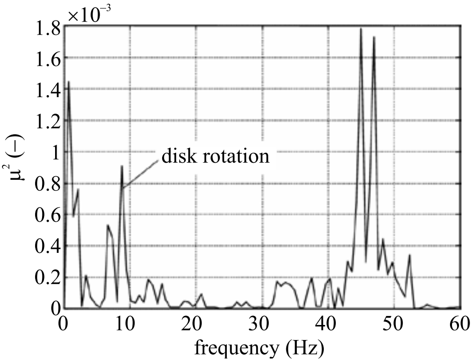

Fig. 7. Power spectrum of the friction coefficient after the contact duration time of 54 min and 40 s

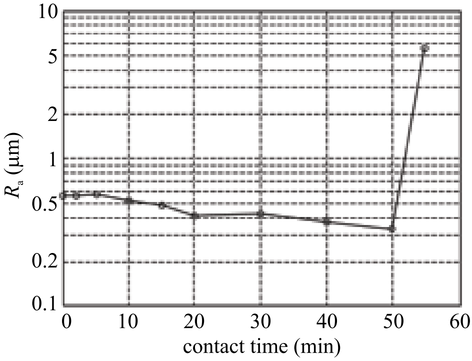

Fig. 8. Variation of the disc average roughness with contact duration time

peak on disc rotation frequency $f \approx 9$ Hz, or $n \approx 540$ rpm. This peak occurs as a consequence of imperfections of the disk (disk eccentricity, misalignment, etc.). During and after the period of TiN coating destruction it is clearly observed an increase of dynamic activities in the contact zone, which is manifested by the appearance of resonance area $f \approx 43$–48 Hz (Fig. 7).

In order to reliably identify the phases of TiN coating destruction, the contact surfaces topography, for both pin and disc were recorded. This was done by Talysurf 6 – Taylor Hobson.

Change of the disk average roughness R_a during the experiment is given in Fig. 8. This diagram has two phases. The first phase is characterised by constant, gentle decline in R_a. This period represents the running-in and steady state stage. After that ($t > 50$ min) a catastrophic wear stage occurs with TiN coating destruction. In this period, the realised type of contact is TiN and STEEL/STEEL.

The changes of the disk and pin surface topography during the experiment are given in Figs 9–13.

By comparison of pin contact surfaces (Figs 12 and 13) one can reliably speak about total destruction of the TiN coating in the period between 50 and 55 min, as well as about drastic worsening of the disc roughness.

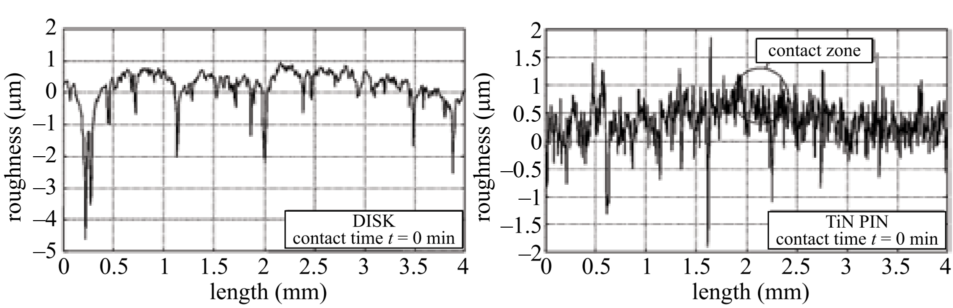

Fig. 9. Surface topography ($t = 0$ min)

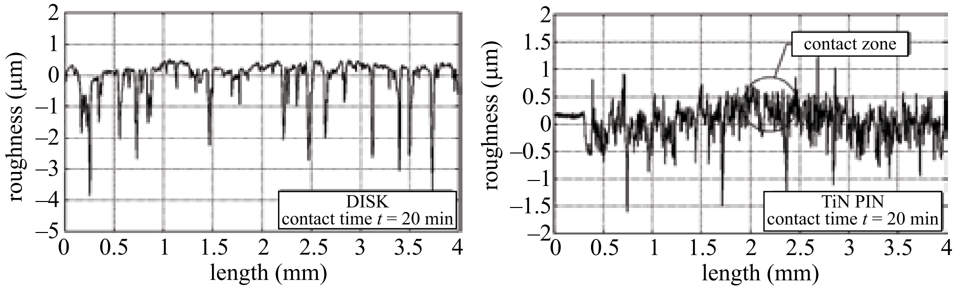

Fig. 10. Surface topography (t = 20 min)

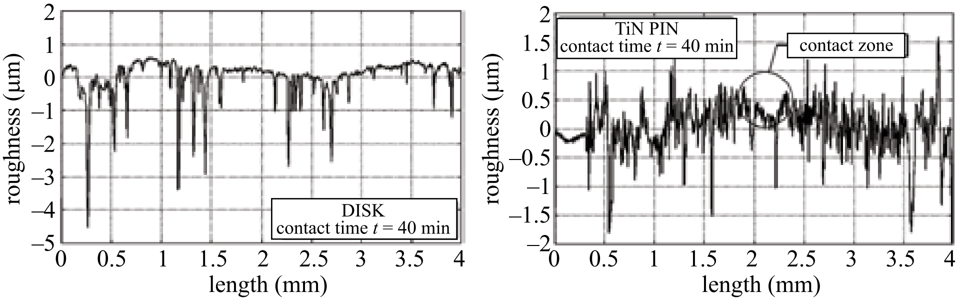

Fig. 11. Surface topography (t = 40 min)

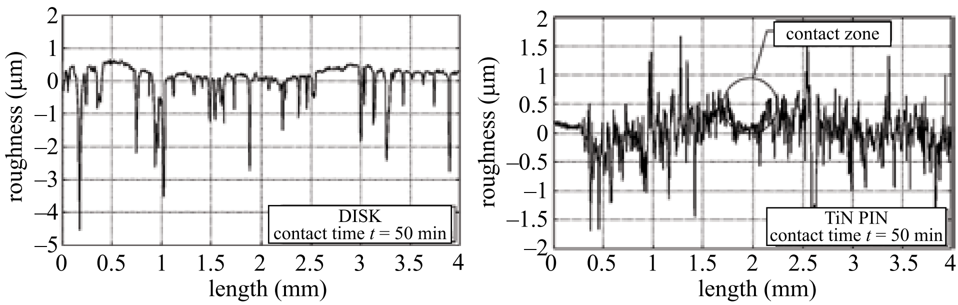

Fig. 12. Surface topography (t = 50 min)

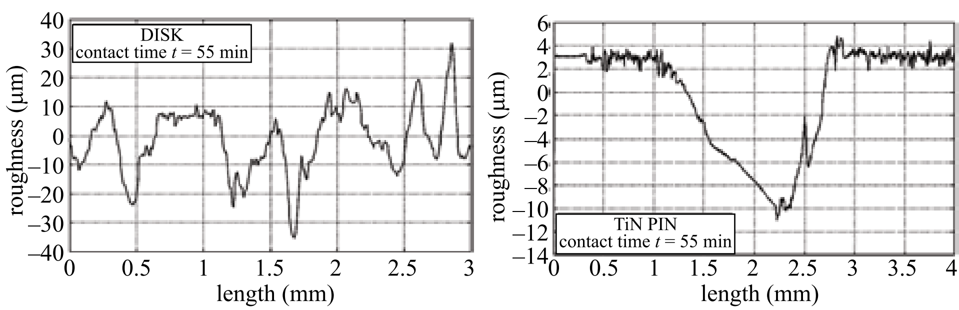

Fig. 13. Surface topography (t = 55 min)

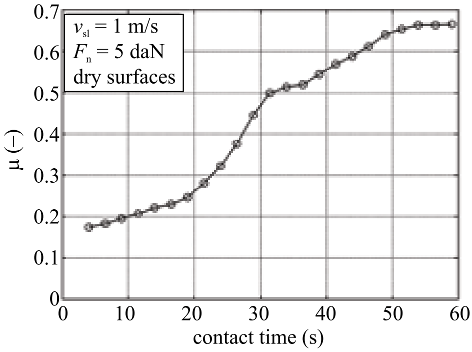

Fig. 14. Friction coefficient as a function of time

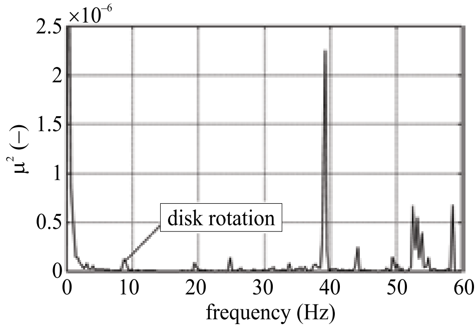

Fig. 15. Power spectrum of the friction coefficient in the period 2–5 s

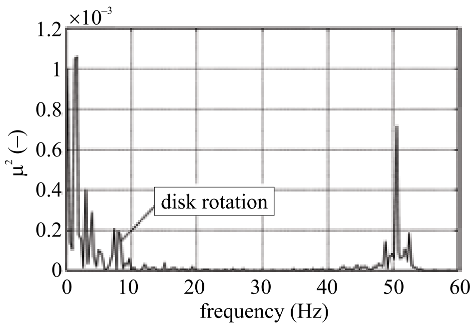

Fig. 16. Power spectrum of the friction coefficient in the period 21–24 s

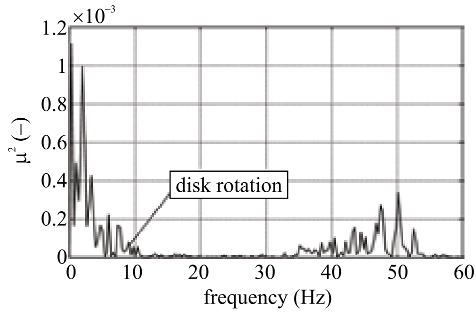

Fig. 17. Power spectrum of the friction coefficient in the period 45–48 s

Dry surfaces. When the matter is the friction process of the dry surfaces, the TiN coating destruction occurs very quickly. This process starts after 20 s. It is manifested by the increase of the friction coefficient (Fig. 14), and the KDB.

At total destruction of the TiN coating, the friction coefficient increased for approximately 4 times, with respect to the beginning.

In different phases of the TiN destruction process the nature of dynamic processes in the contact zone also changes significantly. The changing of dynamic processes in the contact zone was identified with power spectrum (Figs 15–17).

CONCLUSIONS

This paper discussed process of TiN coating destruction on 'pin-on-disk' tribometer. During the experimental investigations the following parameters were considered: friction coefficient, KDF, friction coefficient power spectrum, roughness average and surface topography. Quantification of roughness average and surface topography requires interrupting the continuity of the experiment and disassemble contact elements (pin and disk) from tribometer. Foregoing may be the cause of the appearance of certain errors due to repeated running-in process and establishing tribological balance on micro- and nano-level. On the other hand, other parameters, including KDB, allow the performance of the experiment without interruption and on-line monitoring.

From the aspect of coating condition monitoring, the nature of the TiN coating destruction is almost the same, regardless of that whether the friction process is with or without lubricant in the contact zone. The time from the initial destruction of the TiN coating until its total destruction is short and it significantly depends on the lubrication conditions of the contact surfaces.

From initial destruction of the TiN coating up to its total destruction, the nature of the friction process changes, with dominant presence of dynamic forces in the contact zone. Stability of the friction process, as well as the phenomenon of initial destruction, can be identified by the KDB. This parameter may eventually be used as predictive maintenance tool in TiN coating condition monitoring. KDB parameter can be reliably used for the development of sensors for on-line monitoring of TiN coating destruction in real tribomechanical systems.

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