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Charge sensitive techniques in tribology studies

Streszczenie. *Celem niniejszej pracy było zbadanie zmian występujących na powierzchniach materiałów pod wpływem tarcia za pośrednictwem ciągłej i nieniszczącej metody analizy pracy wyjścia elektronu. W pracy przedstawiono pomiary funkcji pracy wyjścia elektronów określone za pośrednictwem techniki kontaktowej różnicy potencjałów (metoda Kalvin-Zisman'a, metoda bezwibracyjna i kondensatorów jonizacyjnych), oraz doświadczalne zastosowanie tych metod w analizie procesu tarcia. Opracowano techniki badań tribologicznych wykorzystujących sondy ładunku elektrycznego. Przedstawiono przykładowe wyniki pomiarów pracy wyjścia elektronów podczas tarcia, dla próbek ze stali I brązu. Analiza funkcji wyjścia bezpośrednio w trakcie występowania tarcia umożliwiła określenie rodzajów tarcia, dynamiki powstawania defektów, identyfikacji uszkodzeń lokalnych mikrochropowatości oraz ewolucji topologii powierzchni ścieranej.* ***Badanie zmian występujących na powierzchniach materiałów pod wpływem tarcia za pośrednictwem ciągłej i nieniszczącej metody analizy pracy wyjścia elektronu***

Abstract. *The goal of the present work was to study of changes occurring at the surface materials during friction by the continuous non-destructive testing of electron work function. The paper describes the electronic work function measurements by the contact potential difference techniques (the Kelvin-Zisman, the Non-vibration and the Ionization capacitors), and experimental demonstration of the possibility of their application for the analysing of the friction processes. The techniques of tribological studies using charge sensitive probes are developed. Examples of measurements work function during friction for the bronze and steel samples are present. The study work function directly in the process of friction possible to determine the modes of friction and dynamics of defects on the surface friction identify spots of destruction on local microroughnesses, the surface topology evolution.*

Keywords: electron work function, contact potential difference, surface, friction, wear.
Słowa kluczowe: praca wyjścia elektronu, kontaktowa różnica potencjałów, powierzchnia, tarcie, zużycie.

Introduction

The goal of the work was to study of changes occurring at the surface materials during friction by the continuous non-destructive testing of electron work function (EWF).

The methods relies on the sensitivity of the EWF to the various events, which accompany friction, e.g., plastic deformation, creation of new surface of materials, adsorption, oxidation, phase changes and redistribution of alloy components [1-6].

Wear of materials is an unavoidable phenomenon in various machinery, and a good deal of research done to elucidate wear mechanisms [7-9]. The surface layer has the lowest shear stability in a solid part at friction [7]. The dislocations, vacancies and other crystal lattice imperfections generate all the kinds of defects into the material volume, rapidly increases in the metal surface layer with a stress concentration at the boundaries of micro and substructure (interphase and grain boundaries, twins, inclusions, microscopic pores and cracks) [8]. Given that in most cases a material surface works more than the volume, the surface is subject to strict requirements of control. The problems of control of the thin surface layers hold a special interest for tribology [9].

The thickness of the surface layer participates to the EWF measurements, is approximately equal to the interatomic distance for the majority of metals and alloys [2, 10]. Thus, this is almost the only method, which is sensitive to both surface and near-surface defects [3, 6, 11]. The availability of relatively simple techniques and means fostering EWF measurements makes them rather attractive of applying to the studies of surface layer defects mechanisms under a loading directly at friction.

Let us consider charge sensitive technique and experiment results in detail.

Research methods

The charge sensitive techniques (in this case the Kelvin-Zisman, the Non-vibration and the Ionization capacitance probes) for tribological measurements described in the current presentation permits study of only one of the two interacting surfaces during sliding [12-14]. Figure 1 shows a generalized modification of the Kelvin-Zisman technique suitable for friction testing on-line. The probe mounted on the three pin-on-disk machine of the friction testing. These methods is to measure the contact potential deferent (CPD) between the surfaces of sample (M1) and the gauge measuring electrode (M2). The value of the CPD determined by the difference of EWF on the surfaces.

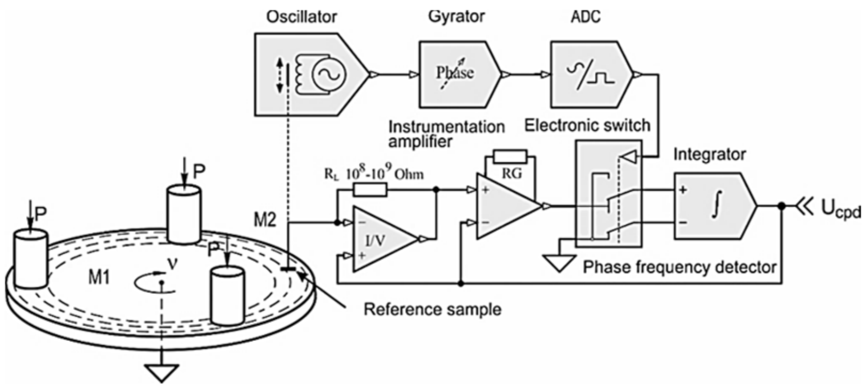

Fig.1. Functional diagram of the system for friction processes monitoring on the electron work function with the Kelvin-Zisman probe

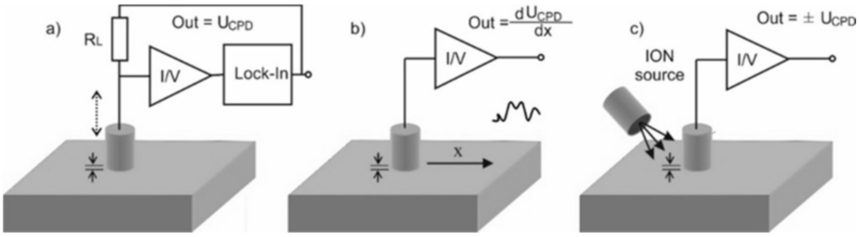

Fig.2. Charge sensitive techniques measurement principle: a) The Kelvin-Zisman capacitor, b) the Non-vibration capacitor and c) the Ionization capacitor

The Kelvin-Zisman method [12] is the most widely applied for EWF measurement. The measuring electrode M2 vibrate by a oscillator and is located at a distance less than 1.0 mm from the rotating sample M2 (Fig. 2a). The alternating current induced by the periodic change in the capacitance is converted to a voltage signal by I/V convertor. The signal comes to the phase detector together with the reference signal from the vibrator. Upon detection, the signal goes to the non-inverting input of I/V convertor and, finally, to the reference electrode to compensate CPD. The circuit maintains an output voltage equal to the CPD. An automatic record of the EWF changes performed.

For a topology study on a surface without determination of the EWF value a technique, the non-vibration capacitance method we used. The non-vibrating capacitor is similar to the Kelvin-Zisman probe. The probe also forms a capacitor between the reference electrode and rubbing surface of sample. However, the probe is moves rather than vibrates over a surface (Fig. 2b) [13]. When the probe electrode moves over a sample surface, the charge on the electrode will change as the sample surface EWF or geometry changes.

Another way to measure CPD is the ion probe technique. It utilizes the radioactive source (Americium) to ionize the gases between the probe and the surface-of-interest, then to form a close loop circuit. Figure 2c shows the schematic of ion probe. The gaseous ions produced carry the current between the two plates when the outer potentials of the two plates are different, and this current detected by means of a galvanometer consisting of a sensitive valve electrometer [14].

All the following sets of meteorological parameters and functional opportunities are refer to these methods, resolution, sensitivity (0.1-1 meV), speed measurement and others, ensuring the performance of measurements depending on the particular object and studies subject.

We can be used the Kelvin technique in three experimental modifications [5].

The most widely used method is to record the average integral value of CPD over a specific period of time (rpm). This recording scheme allows for tracing of the EWF changes in the long-term tests.

The second method is to record a signal from the Kelvin probe at one point of friction surface. Equipment for synchronization of counts with a sample position is required. The use of this scheme allows updating in real-time mode about operating process of friction from different sensors at one point of test surface (the work function, friction force, temperature, etc.).

The third method is to record the potential distribution throughout the friction track or some macro area. Equipment for synchronization of counts with a sample position is also required. However, this scheme is possible through the usage of the Non-vibration capacitance probe.

As an example below, we present a photo of the system with Non-vibration probe for EWF measuring of the friction surface – Fig.3.

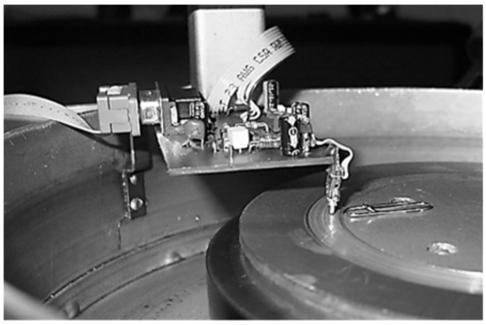

Fig.3. The modification of the Non-vibration probe for friction testing

The devices for the CPD measurement in the dynamics of the friction should meet high requirements concerning a noise reduction and stability of operation since high level of vibrations, acoustic and electromagnetic noise originate from the friction test machine. We have previously carried out additional research of requirements for friction machines and for CPD techniques, results presented in the papers [12]. The recommendations to reduce of the CPD measurement errors presented in the papers [4, 15].

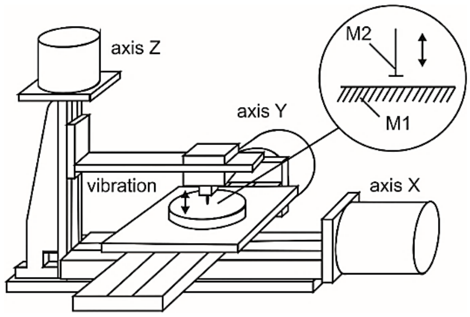

Fig.4. The schematic diagram of the Scanning Kelvin-Zisman probe

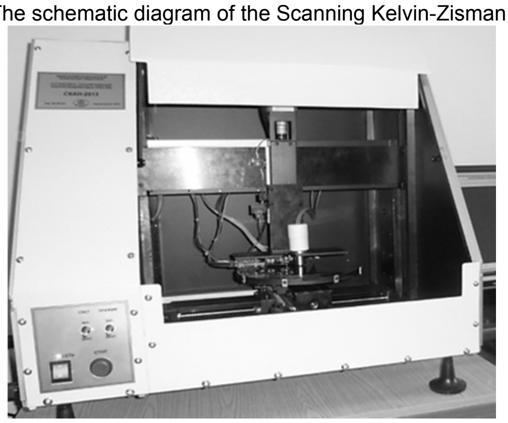

Fig.5. The modification of the Scanning Kelvin-Zisman probe devise for testing of the electron work function (or contact potential different) distribution

In case the study of the distribution of the surface EWF, we used the Scanning Kelvin Probe (SKP) [1]. In the SKP the spatial distribution of CPD values is determined by mechanically scanning the vibrating probe over the sample surface. Design of the macroscopic SKP in general case is very similar to described above for a case of friction surface monitoring. Scanning performed by moving the working table using the XY drive. The spatial resolution determined by the size of the probe (~1 mm for results described below).

In Fig.4 and Fig.5 the schematic diagram and photo respectively of the SKP with the Kelvin-Zisman capacitor for inspection applications functionality a shown.

Results and discussion

The study of the friction surface EWF in response to the normal load carried out in the following manner. Discs samples with diameter of 100 mm and thickness of 4 mm were tested at a constant sliding velocity (3,2 m/s) in oil and at dry friction on a three-pin friction apparatus AE-5 equipped with a rubbing surface function continuous monitoring device and with the friction moment and volume temperature recorders. Steel 45 (40–45 HRC) pins with diameter of 8 mm were the majority of counterbody.

Test operating cycle was started at 0.25 MPa then the load was increased in steps to 1 MPa. The registered parameters leaped at each stage after intermediate loading due to the processes of additional wear-in and surface adaptation. Therefore, the subsequent loading steps performed only after the stabilization of the registered parameters and corresponding readings taken based on their stabilized magnitudes at a given load. The experimental points reconstructed into EWF responses to the normal load as it shown in Fig. 6.

The studies have revealed that the friction surface EWF dependency layout is like the normal load and has 3 specific sections (Fig. 7). EWF increasing together with the normal load increasing is faces on section I. Then the curve progress changes and the friction surface EWF decreases on section II. At dry friction, sections I and II are located in a very low loads area which is commonly have no practical applications (less than 0,05 MPa). The EWF value is ceases to degrease when the load increases, and even it increases in some cases, when further load incrementing, section III. The friction moment and volume temperature increase abruptly at the seizure and EWF strongly reduces at the same time.

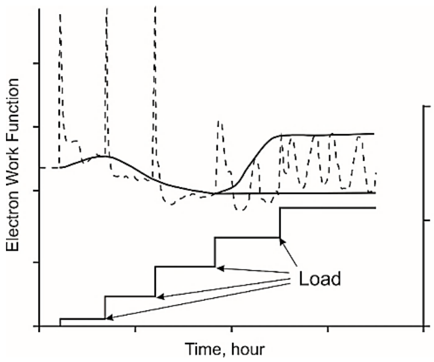

Fig.6. A typical test circuit

Fig. 7 shows that the moment of friction and the surface temperature increase monotonously within the given range of loads without any extremes correlated with the function behavior. Hence, surface layers changes, which are not clear bases on external friction parameters (the friction torque and volume temperature) may be revealed by the dependencies of surface EWF variations.

Within the third zone described above, the kinetics of steady state friction characterized by regular periodic changes of the rubbing surface EWF integral value (for example – Fig.11). The period, amplitude and harmonic contents of such changes determined by the properties of materials and testing conditions. The periodic changes observed in the cases of reciprocated and lubricated friction also.

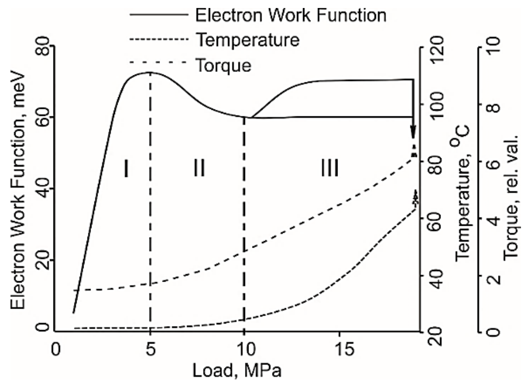

Fig.7. Bronze rubbing surface electron work function, torque and surface temperature vs. normal load curves

It should also note that during a testing in the conditions of friction boundary the oil type substitution, holding all other factors constant, merely resulted in the displacement of the critical points that separate specific sections while maintaining the dependency general character.

Fig.8 and Fig.9 shows the surface maps of EWF distribution the initial iron GI30 sample surface (Figure 6a) and on the macro area of friction after running-in at the low-loads area (0.025 MPa, Figure 6b) when a metal surface layer transformation from predominantly elastic deformation to predominantly plastic deformation.

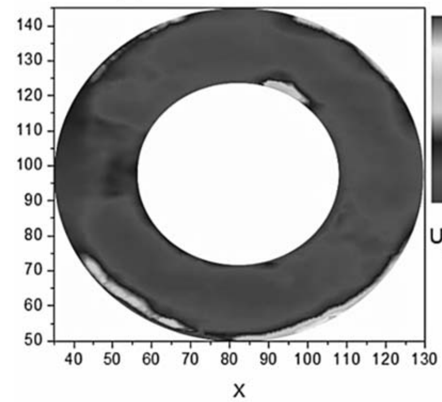

Fig.8. The contact potential difference distribution on steel sample initial surface registered by Scanning Kelvin-Zisman probe

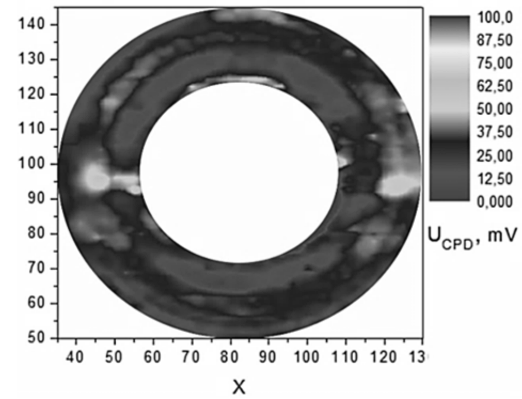

Fig.9. The contact potential difference distribution on friction surface of the steel sample at the normal pressure of 0.025 MPa registered by Scanning Kelvin-Zisman probe

It is clear from the presented results. The original surface has more smooth EWF distribution (Fig. 8). EWF distribution on a friction track difference faces and EWF local extremes, obviously corresponded to a local plastic deformation, appear after 2 hours of testing at the speed of 3.2 m/s and the normal load of 0.025 MPa (Fig. 9). These results we have obtained by modified SKP device.

Thus, the distribution of the surface EWF depending from the friction shows that during the friction in areas where prevails severe plastic deformation (crushing projections surface, gouging, etc.) occurs the local lowering of EWF on the friction track.

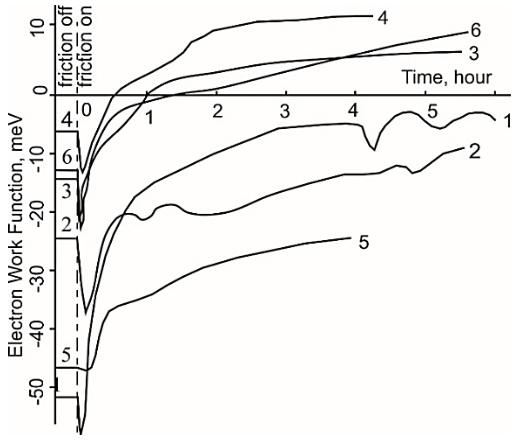

Fig.10. Variation of the integral value of rubbing surface work function with time for some materials (1 – brass; 2 – bronze (Al); 3 – bronze (Sn); 4 – commercial copper; 5 – stainless steel; 6 – medium carbon steel) at load 0.05 MPa

Fig. 10 shows the variation with time of the stationary friction of the surface EWF for some materials at load 0.05 MPa. At the initial friction contact, a sharp decrease followed by a sharp increase of the EWF relative to the initial value. Our interpretation is that the initial transients correspond to changes in the original oxide or other surface layers and running-in of the sliding surfaces. After a certain time, which depends on material properties, the friction regime stabilizes. From Fig. 10, one can find running-in finishing and the beginning of steady state friction conditions. Investigation of the kinetics of friction showed that in many cases the periodic changes in the EWF of friction surface within trials time. The change of the EWF have a pronounced periodic character when increasing the test cycle. In Fig. 11 shows the variation with time of the stationary friction of the surface EWF at load 0.12 MPa.

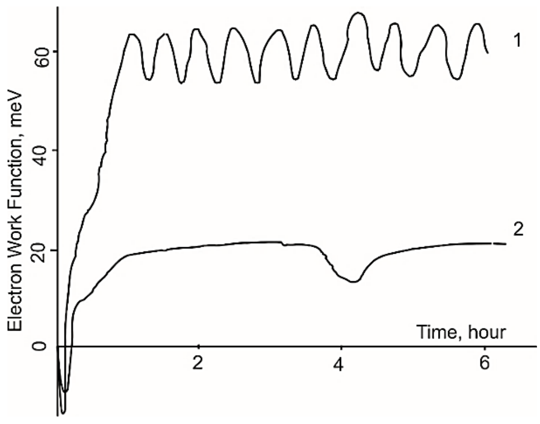

Fig.11. Variation of the integral value of rubbing surface work function with time for some materials (1 – brass 37-63; 2 – stainless steel 12X18H10T at load 0.12 MPa. In these case an initial values of electron work function zeroed for both metals

The friction mechanisms in detail could be determined by the study of EWF topology evolution with the friction duration value. The topology of friction surface EWF distribution depending from the friction time value registered by the non-vibrating probe and presented in the Fig. 12.

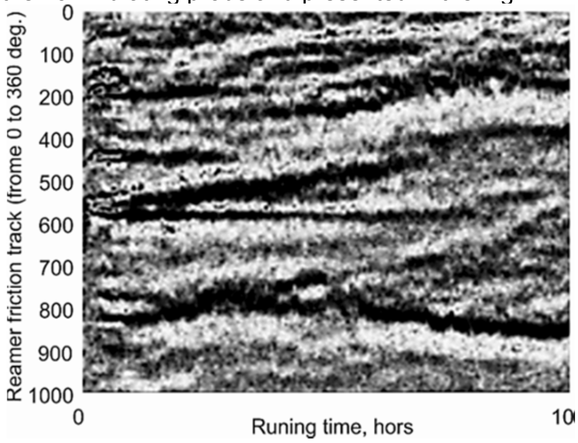

Fig.12. Rubbing surface work function topology evaluation as a function of time of friction registered by the Non-vibrating probe at the speed of 3.2 m/s and the normal load of 0.05 MPa

Analyzing the EWF evolution on the friction track, we can judge on the processes of deformation and destruction of the material surface layer. The statistical parameters (range, variance, and others.) distribution of the RWE essentially depend on the mechanisms of deterioration of materials. The destruction processes on the area of increasing of the EWF and a healing process on the area of decreasing the EWF.

Conclusion

The described charge sensitive techniques is applicable for investigations and analysis of a wide range of processes involving rubbing surfaces, including running-in processes, formation and depletion of lubricating layers, responses of a surface to variations of friction conditions, fatigue processes, etc. It used to investigate tribological materials for a wide range of conditions including changes in load, sliding speed and environment with or without lubrication materials.

Based on the experimental data can be assumed that the response of the EWF to pressure reflects the modifications of the physical and chemical behavior of a friction surface. It allows apply the advanced techniques of the continuous contactless monitoring of SEWF of a friction surface for the identification a section within which a given friction process evolves together with the critical points of the process. The critical points allow com-pare the performance of the various materials of friction couples and optimize their chemical and phase composition as well as lubricants.

The results for the sliding contact case allow assume that the responses of the function dependency layout is like the normal load changes during transition from the section II to the section III (Fig. 5). It characterize the maximum permissible working pressure which a material can certainly withstand without failure, since operation within portion III is incumbent with the appearance of structural defects in the surface layers (micropores and microcracks). The protracted tests do not cause any friction surfaces failure when they operate under loads within sections II and I. Hence, the normal load of transition from section II to section III can selected as the criterion of materials applicability for friction units. Materials should not be used under loads corresponded to section III, since in this case the friction process produces failure centers in surface layers. Therefore, the load of transition from section II to section III is the objective criterion for materials applicability evaluation in friction units and, as it demonstrated above, this criterion is applicable to a wide variety of materials.

Investigation of the kinetics of friction showed that in many cases the periodic changes in the EWF of friction surface within trials time. The change of the EWF have a pronounced periodic character when increasing the test cycle.

Investigating of the EWF evolution on the friction track, we can judge on the processes of deformation and destruction of the material surface layer. The statistical parameters (range, variance, and others.) distribution of the RWE essentially depend on the mechanisms of deterioration of materials. The destruction processes on the area of increasing of the EWF and a healing process on the area of decreasing the EWF.

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