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Charge sensitive techniques in control of the homogeneity of optical metallic surfaces

Abstract. *The aim of the work was to study electrophysical states of optic surfaces of non-ferrous metals and alloys in relation to geometric and physic-chemical parameters according to the distribution of the electron work function over the surface. We conducted the study on experimental metal samples made of copper and aluminium alloy, machined in accordance with the nanodiamond machining technology. Modernized Kelvin probe used as the registration technique of the changes of the electron work function over the surface. Dependence between the electron work function value, as well as its alteration and the physic-chemical and geometric parameters of a surface has been determined. It has been shown that the nanodiamond machining technology makes it possible to obtain electrophysically uniform optical surfaces on copper and aluminium alloy with the minimal range of the distribution of the electric potential over the surface.*

Streszczenie. *Celem pracy było zbadanie elektro-fizycznych stanów optycznych powierzchni metali nieżelaznych i ich stopów, w odniesieniu do parametrów geometrycznych i fizyko-chemicznych, zgodnie z podziałem funkcji pracy elektronów na powierzchni. Przeprowadzono badania na próbkach eksperymentalnych metalowych wykonanych z miedzi i stopu aluminium, obrabiane zgodnie z technologią obróbki nanodiamentu. Zmodernizowaną sondę Kelvina zastosowano do techniki rejestracji zmian w pracy wyjścia elektronu na powierzchnię. Określono zależności między wartością pracy elektronów, jak również ich zmiany fizyko-chemiczne oraz parametry geometryczne powierzchni. Wykazano, że technika obróbki nanodiamentu umożliwia uzyskanie jednakowych elektro-fizycznych stanów optycznych powierzchni z miedzi i stopów aluminium do minimalnego zakresu rozkładu potencjału elektrycznego na powierzchni. (**Czułe techniki ładowania w kontroli jednorodności optycznych powierzchni metalowych**).*

Keywords: diamond nanomachining, electron work function, surface electrostatic potential, Scanning Kelvin Microscope, roughness.
Słowa kluczowe: diamentowa nano obróbka skrawaniem, funkcja pracy elektronów, powierzchniowy potencjał elektrostatyczny, skanowanie mikroskopu Kelvina, szorstkość.

Introduction

Surface electrostatic potential is a universal parameter, which contains information on chemical, structural, electrical and other material properties [1]. The electron work function (EWF) makes a crucial contribution to the formation of surface potential relief for metal and semiconductor materials. The EWF is very sensitive to different events, which accompany the fabrication of metallic surfaces with optical purity: plastic deformation, oxidation, redistribution of surface and near-surface defects and other [2, 3].

The existing theory of dimensional machining based on using of integral parameters of machined surfaces, for example, maximum height of the profile R_t. As it is known, there is a high density of free electrons in metals. Technological impact of a cutter in the machining and formation of optical surfaces non-ferrous metals and alloys results in oxidation processes and changes in physic-chemical parameters of surface [4]. The thickness of the formed oxide film can be comparable to the maximum height of roughness or more. Control of only geometric parameters is insufficient to describe characteristics of machining and formation of real ultra-smooth metallic surfaces. All surface imperfections should be taken into account for the control of machined metallic surfaces. The inhomogeneity of the surface layer has a great influence to the distribution of electrons and leads to the electron emission and smoothing the electron density effects [5]. According to the electronic theory of metals, electron energy is as lower as more homogeneous and smoother is the surface. The oxidation processes on the metallic surface change its EWF [6]. It is governed by the electron transfer at the formation of bond between oxide layer and the surface dipole layer. The EWF change of the metallic surface is directly proportional to their effective electrical dipole moment and the degree of surface oxidation. The high sensitivity of the EWF to the surface inhomogenity has led to wide use of this parameter for the study of the oxidation [5, 6] and other processes in surface layer [2, 7, 8]. Therefore, the EWF can be used for complex evaluation of mechanical, chemical and physico-chemical parameters of machined surfaces.

The aim of the work was to study electrophysical states of optic surfaces of non-ferrous metals and alloys in relation to geometric and physic-chemical parameters according to the distribution of the electron work function over the surface.

Materials and Research methods

We conducted the study on experimental metal samples made of copper and aluminum alloy, machined in accordance with the diamond nanomachining technology. The nanodiamond machining technology would be capable of ensuring the roughness of non-ferrous metals and alloys machined at the level of $R_a \leq 0{,}005$ μm. The machining technology of samples substrates includes a preliminary turning or milling followed by heating to stabilize the phase and structural state of the material, removal of internal stress, optimizing resistance to plastic deformations. Superfinishing processing of substrate surfaces is carried out on MC 6501 precision lathe with a vertical spindle. The cutter made of single crystal synthetic diamond STM "Almazot" was specially designed and used as a tool. Nanodiamond machining takes place at the crystalline, and the deformation of grains of material is almost non-existent thorough description of the instrument and operating principles is given in [9]. Reference designations and descriptions of the experiment samples presented in the Table 1.

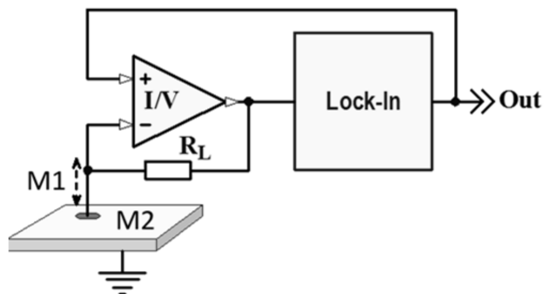

Fig.1. Kelvin-Zisman probe measurement principle

The EWF distribution was registered by the upgraded Kelvin probe [2]. The method is to measure the contact potential deferent (CPD) between the surfaces of sample and the reference measuring electrode. The value of the CPD is determined by the difference of EWF on the surfaces of formed plane capacitor. The value of the CPD is determined by the difference of work functions on the surfaces of formed plane capacitor. The metal plates *M*1 and *M*2 (see Fig.1) form a parallel-plate capacitor of capacitance C.

Table 1. Reference designations and descriptions of the experiment samples with surface, machined in accordance with the diamond nanomachining technology

Reference designation	Samples description
a1	Porous anodic alumina oxide (*PAOA*) having a diameter of 100 mm and thickness of 1.5 mm
a2	*PAOA* Aluminum with nanodiamond galvanic coating sample having a diameter of 50 mm and thickness of 10 mm
b1	*AMG*-2 Aluminum having a purity grade of 10, diameter of 100 mm and thickness of 1.5 mm
b2	*AMG*-2 Aluminum having a purity grade of 14, 100x50x7 mm and thickness of 1.5 mm
c1	*M*2 copper having a purity grade of 12, having a diameter of 25 mm and thickness of 10 mm
c2	*M*2 copper having a purity grade of 14, 30×25×2 mm and thickness of 1.5 mm

The stipulated CPD charge *Q* on the capacitor will be. The gap between the capacitor plates periodically changes due to the vibration of one of the plates (introduced be Zisman). The capacitance periodically varies and an alternating current varies with the frequency of plate vibration. A source of compensation voltage is included, the output of which can be adjusted so that it will compensate the CPD. In this case:

(1) $$Q = C(U_{CPD} + U_{comp}) = 0$$

The fundamental equation that characterizes Kelvin probe current response is given as:

(2) $$i = \frac{dQ}{dt} = \frac{d(CU_{CPD})}{dt} = C\frac{dU_{CPD}}{dt} + U_{CPD}\frac{dC}{dt}$$

The Kelvin-Zisman method results in current flow by vibrating the probe relative to the surface of interest. The Kelvin probe is generally fixed in position above a surface in quasi-equilibrium, so the dU_{CPD}/dt term is assumed to be negligible.

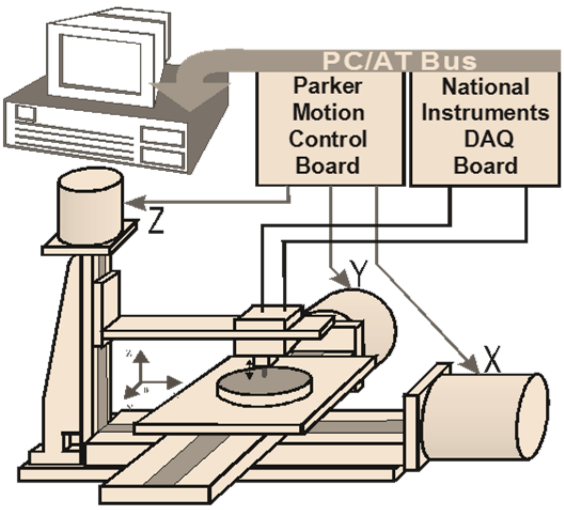

Fig.2. Scan station

Probe is made of a material with a relatively stable EWF (in this case of nickel). For the move from the recorded value of CPD to the relative value of EWF, it is necessary to reverse the sign of measured values.The measurements were carried out on special scan station (see Fig.2) [2].

The station consists of the following main components: XY drive of working table; control and data acquisition unit made on the basis of a standard PC; Kelvin-Zisman vibrating probe. The drive allows movement of the table with attached to it sample of 180x180 mm, the step of scanning is 10 µm. Registration of contact potential differences was carried out in a range of ± 5 mV and resolution of 250 µm. Random measurement errors were reduced to zero [10].

What is special about the methodology of this study is non-contact, the absence of destructive external actions and the possibility of identifying structure defects that are inaccessible to other non-destructive, in particular, optical and electronic methods.

Results and discussion

Analysis of work function distribution for precision surfaces makes it possible to detect the heterogeneity of their electrical properties reflecting distribution of surface defects. The registered value of electrostatic potential variation on the surface will indicate the heterogeneity of electrical and physical properties of the surface. The results of measuring the relative variations of work function on their surfaces shown in the Table 2.

Table 2. Measuring results of relative value of electron work function

Sample	$(\Phi_{probe}\text{-}\Phi_{sample})_{min}$, meV	$(\Phi_{probe}\text{-}\Phi_{sample})_{max}$, meV	ΔU, mV
a1	60	125	65
a2	0	45	45
b1	–320	–270	50
b2	–305	–300	5
c1	–25	-15	10
c2	0	5	5

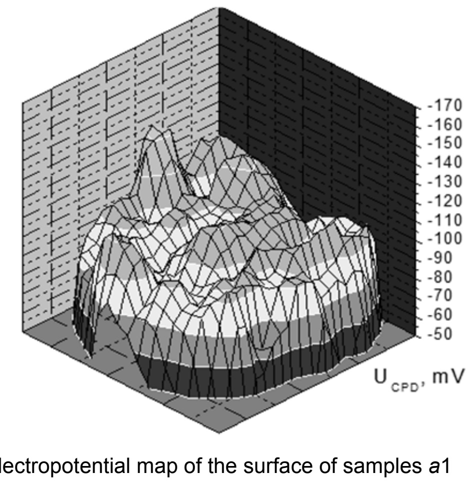

Fig.3. Electropotential map of the surface of samples *a*1

As can be seen from these results, the relative maximum value of EWF is 125 meV and the change in electric potential on the surface is ΔU = 65 mV for porous anodic alumina oxide (*PAOA)*, sample *a*1.The visualized images of electric potential relief of the surface of sample *a*1 are presented in the Fig.3.

Electropotential image of the surface of disk of *PAOA* with nanodiamond galvanic coating (sample *a*2) shown in the Fig.4. Heterogeneity of electrical properties of the surface appears to change the values of the potential are visible in the image.

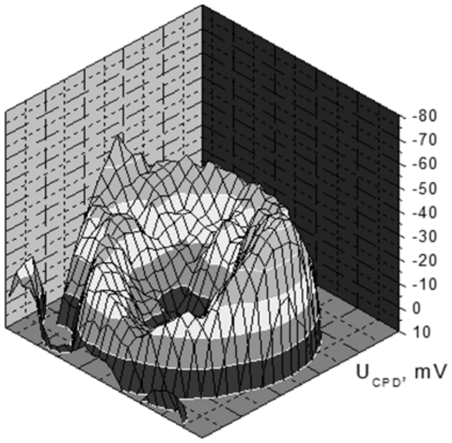

Fig.4. Electropotential map of the surface of samples *a*1

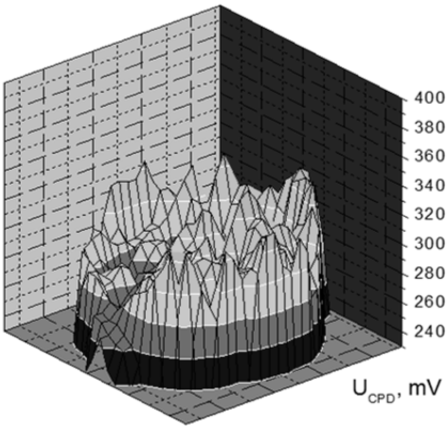

Fig.5. Electropotential map of the surface of samples *b*1

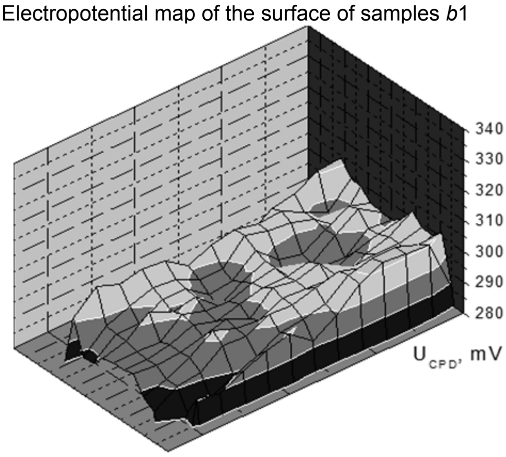

Fig.6. Electropotential map of the surface of samples *b2*

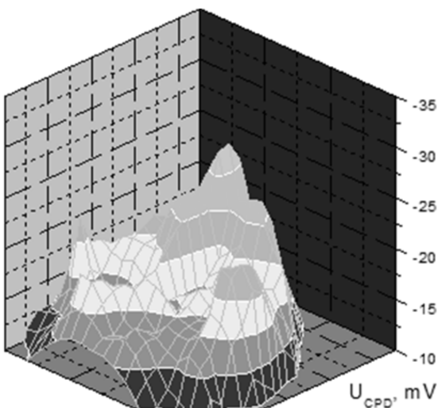

Fig.7. Electropotential map of the surface of samples *c*1

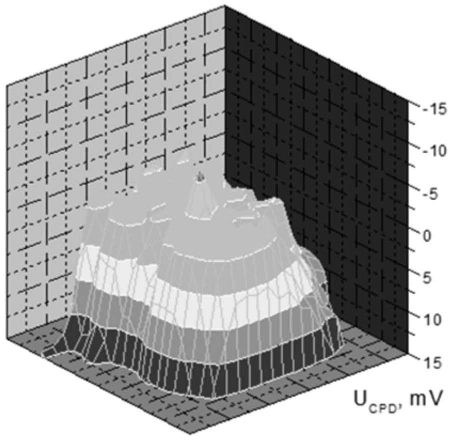

Fig.8. Electropotential map of the surface of samples *c*2

In comparison with the sample *a*2 PAOA (Fig.4) distribution of electric potential is more uniform, the maximum recorded energy of EWF was 45 meV and the change in electric potential on the surface is ΔU = 45 mV. Based on these images we can come to conclusion about degree of heterogeneity of surfaces of the porous anodic oxide layer and its impact on the nature of EWF distribution on nanodiamond galvanic coating.

Aluminum alloy substrates, samples *b*1, *b*2 (Figs. 5 and 6) have minimum values of EWF -320 meV, -265 meV respectively and it does not depend on class of surface finish which is contrary to the assertion the surface more smooth, the EWF less. The results say otherwise. Not only the numeric value of EWF but also the changes of electric potential on surface ΔU significantly characterizes the class of surface finish, roughness and electrical and physical homogeneity.

The Fig. 7 shows the electropotential image of the *M*2 copper (sample *c*1) with the class of surface finish of 12. The Fig. 8 show electropotential image of surfaces of the *M*2 copper (sample *c*2) respectively processed according to the diamond nanoturning technology with the class of surface finish better than 14.

Registered range of EWF for samples *b*2 and *c*2 had minimal values of 5 mV and 5 mV respectively indicating the high level of electrophysical homogeneity of the surface layer achieved by the diamond nanoturning technology.

Conclusion

Studies have shown that during the nano processing of metal surface including nanodiamond machining technology, electron work function and its change on the surface characterize its physical and chemical state and in conjunction with its geometric characteristics, especially roughness, allow to monitor the achievement of specified performance of processed products, to define and optimize the technological modes of processing.

High electrophysical homogeneity of surface layer with a minimum value of work function and a minimum range of electric potential on the surface at ΔU = 5 mV and ΔU = 5 mV have been received during the nano diamond processing of the *AMG*-2 aluminum alloy and *M*2 copper respectively.

The application of nanodiamond machining technology followed by anodic oxidation with the application of nanodiamond coating provides a uniform thermal material.

The proposed charge sensitive method for monitoring of the distribution of electron work function can be used for manufacturing optical components for semiconductor lasers and for other precision parts based on aluminum and copper alloys with increased energy characteristics.

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