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# Multifractal analysis of the $TiN/Al_2O_3$ coating surface under HCEB modification.

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New experimental results are presented on the structure and phase composition of hybrid coatings, which were deposited on a substrate of AISI 321 stainless steel using a combination of plasma-detonation and subsequent High-Current Electron Beam (HCEB) treatment. Modes of processing at which the remelting of the material, which allows to obtain high adhesion of protective layers to the substrate surface are selected. Statistical parameters are calculated within two dimensional multifractal detrended fluctuation analysis. It is shown that the generalized Hurst exponent of the surface under modification is determined by a beam current.

**Keywords:** Self-similarity, Hybrid coatings, Fractal dimension, Hurst exponent.

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## 1. INTRODUCTION

Nowadays, one of the most effective directions of modifying the surface properties of plasma-detonation acts as a technology that allows to receive protective coatings hybrid [1]. An oxide-aluminum ceramics and other coatings based on titanium carbide and tungsten carbide and nitrides possess a number of useful properties, which are able to provide corrosion protection, high hardness and mechanical strength low wear and good electro-isolation properties. Additional treatment of these coatings by high-current electron beams (HCEB) in the regime of partial melting results in ablation of surface impurities and activations of the coating surfaces [2]. Deposition of a TiN-layer, also showing high-melting temperature, hardness and corrosion resistance, additionally allows the decrease of the surface porosity of the oxide coatings and the enhancement of the protective action.

The surface of the materials obtained by different methods of deposition usually has a self-similar structure. The self-similarity means that the each segment of the initial set has the same structure as the whole object. The properties of these objects can be described by the theory of fractals, using special parameters, like fractal dimension (or set of dimensions or multifractal spectrum in case of complex structures), Hurst exponent and other [3]. In our work we introduce the investigation of the self-similar structure of the hybrid coating $TiN/Al_2O_3$ by numerical method of two dimensional multifractal detrended fluctuation analysis. Our calculation allows to present a quantitative characteristic of the surface roughness, and to compare it for different part of the sample.

## 2. SURFACES UNDER INVESTIGATION

The protecting hybrid coating $TiN/Al_2O_3$ was formed on the substrate of austenite stainless steel AISI 321. The aluminum oxide coating was formed using a high-velocity pulsed-plazma jet from the facility “Impuls-5”[4]. $\alpha$-$Al_2O_3$ powder with average grain dimensions 28 to 65 um was used as initial material.

This technology applied for production of the protecting coatings is relatively new and based on electromagnetic acceleration of burning products from gas mixtures (propane, oxygen and air). Approaching such an electric conducting layer the aluminum oxide powder is quickly heated and accelerated in the flow of pulsed plasma. At the moment when the pulsed plasma jet is ejected from the plasmatron the electric circuit is closed between an eroding electrode and the substrate surface. In the closed system a pulsed magnetic field in which temperature of the plasma-powder flow was increased for the second time, was formed.

Using the facility “Bulat-3T” with vacuum-arc sources (Kiev, Ukraine) TiN layer was deposited with the goal to increase the corrosion resistance to protective ceramic coatings and to avoid disadvantages of powder deposition i.e. porosity and roughness [5].

It is known [6] that aluminum oxide ceramics and materials on titanium carbide and nitride are widely applied for corrosion protection. But their chemical instability in some aggressive media depends both on electron structure features and on the amount of pores formed. Therefore to provide bulk degassing of coatings and mass transfer processes in the “coating-substrate” interface, we melted the hybrid coating surfaces by high-current electron beam under various regimes (including melting). It allowed on to heal micropores and to stimulate the diffusion processes between deposited panicles and layers. It was found that electron beam melting of the hybrid coating surfaces $TiN/Al_2O_3$ (20 mA beam current) was accompanied by partial melting of the non-uniformities occurred in the surface structure (Figure 1, a). The coating had a layered but melted structure. Repeated HCEB melting of the coatings induced essential (even visible) changes in the surface relief (Figure 1, b-d).

During the second stage of melting the geometry of hybrid coatings surface layers depended on the electron beam power density. Correspondingly, the higher it was, the better these hybrid coatings surfaces mixed and the more uniform they became. The 35 mA beam current fully sealed the produced craters in the surface, and its roughness essentially decreased.

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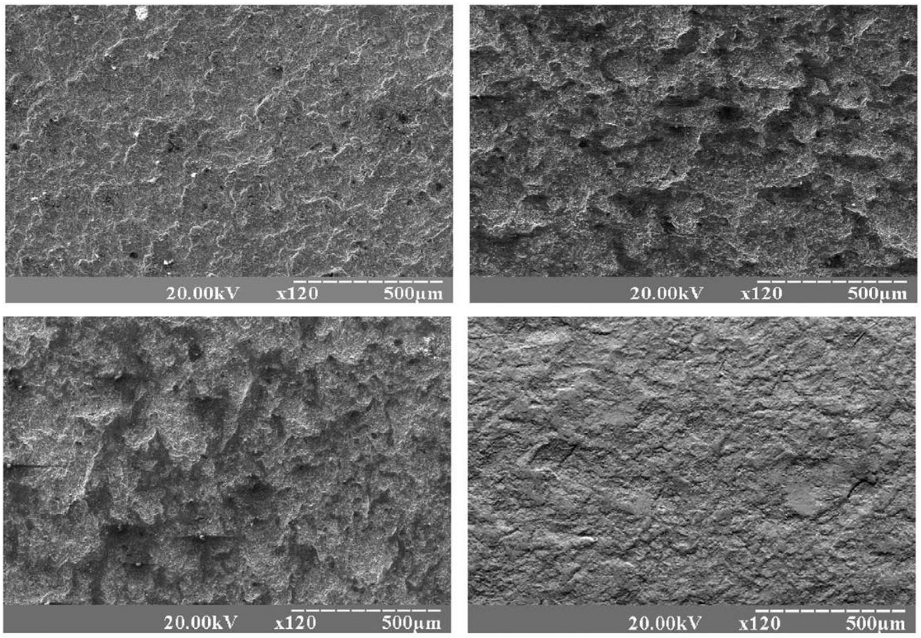


**Fig. 1** – HCEB effect on $Al_2O_3$/TiN hybrid coatings surface. The beam current in electron beam quenching of coating surfaces was respectively: a – 20mA, b – 20+15mA, c – 20+25mA, d – 20+35mA

## 3. TWO-DIMENSIONAL MF-DFA

All surfaces were investigated within two dimensional multifractal detrended fluctuation analysis (MF-DFS). The standard procedure oh this method is presented by the following stages [7]. The overall detrended fluctuations is calculated, that is

$$F_q(s)=\left\{\frac{1}{M_sN_s}\sum_{v=1}^{M_s}\sum_{w=1}^{N_s}\left[F(v,w,s)\right]^q\right\}^{1/q}, \qquad (3.1)$$

where $q$ can take any real value expect for $q = 0$. When $q = 0$, we have

$$F_0(s)=\exp\left\{\frac{1}{M_sN_s}\sum_{v=1}^{M_s}\sum_{w=1}^{N_s}\ln\left[F(v,w,s)\right]\right\}, \qquad (3.2)$$

Varying the value of $s$ in the range from $s_{min} \approx 6$ to $s_{max} \approx min(M,N)/4$, we can determine the scaling relation between the detrended fluctuation function $F_q(s)$ and the size scale $s$, which reads

$$F_q(s) \sim s^{h(q)}. \qquad (3.3)$$

where $h(q)$ – Hurst exponent.

If the object under investigation has a self similar structure, the dependence (3.1) must be linear in logarithmic scales. Figure (2) illustrates the dependence of the detrended fluctuation $F_q(s)$ as a function of the scale $s$ for different values of $q$ marked with different symbols.

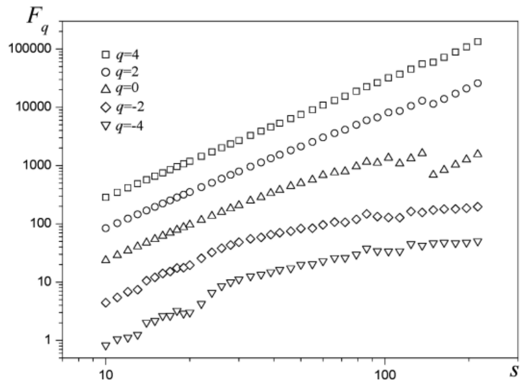


**Fig. 2** – Log-log plots of detrended fluctuation function $F_q(s)$ versus the lag scale $s$ for five different values of $q$

The collapse of the data points on the linear lines indicates the evident power law scaling between $F_q(s)$ and $s$, which means that the surface of hybrid coating is self-similar.

The dependence of the Hurst exponent received for different beam current density is shown in Figure (3).

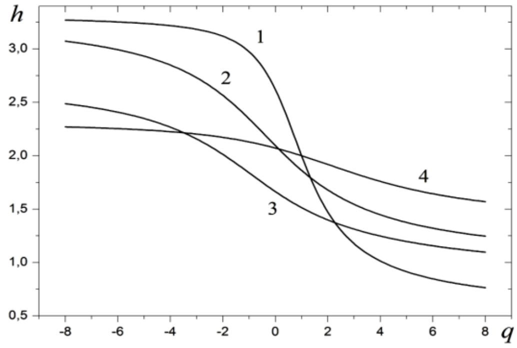


**Fig. 3** – The dependence of the generalized Hurst exponent of the hybrid coating $Al_2O_3$/TiN surface on the beam current density

From these relationships it can be seen that all surface of coating exhibit multifractal behavior. It is especially shown at not high values of the beam current density of 20+35 mA. Range of Hurts exponent is maximum value at this current. Approaching the monofractal behavior is noticeably when the beam current 20+35 mA. In this case the range of Hurst exponent becomes minimal. That change of the range shows dependency of the geometry of the surface layers of the hybrid coatings on the electron density of the beam power. Accordingly, at the higher beam current mixing of the hybrid surfaces is better and they become more uniform surface. As a result, there is decrease of surface roughness.

## 4. CONCLUSION

Performance of mechanical studies demonstrated that hybrid coatings based on corundum and titanium nitride, which were modified by an electron beam until melted, had notably better servicing characteristics. Therefore this technology could be applied to solve technical problems (for example, to decrease wear, to protect from corrosion, to increase adhesion and to improve nano- and micro-hardness).

Quantitative parameters of the surface structure obtained by the numerical analysis procedure can be used to characterize the topology of interface under modification. As shown by the numerical analysis, the microscopic roughness of the surface is smoothed with a gradual increase in current density electron beam.

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