

## Abrasive Wear Resistance of Electrosark Coatings on Titanium Alloys

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### ABSTRACT

According to most researchers, improving the tribological characteristics of titanium alloys at this stage is most appropriate through surface modification tribotechnologies. In the present work, the qualitative characteristics of coatings of tungsten-free hard alloy materials based on TiC, TiN TiCN TiB<sub>2</sub>, applied on the most popular titanium alloy Ti6Al4V by electrosark deposition with low pulse energy are investigated. The influence of the electrode materials, the process parameters, the characteristics of the coatings and the roughness parameters on their wear and abrasion resistance has been studied. It was found that the use of coatings from the studied electrodes shows an increase in abrasion resistance by 1.5 - up to 3 times compared to that of the substrate and the electrode materials and process parameters were determined, in which maximum wear resistance was obtained.

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### 1. INTRODUCTION

The main disadvantage of titanium alloys are their bad tribological properties - unstable coefficient of friction, tendency to adhesion, micro-welding and abrasion, tendency to set and oxidize at temperatures above 500°C, intensive wear and destruction [1-4]. This sharply limits and even makes dangerous the application of these attractive alloys in friction joints. According to most researchers, improving the tribological characteristics of titanium alloys at this stage is most appropriate through methods for surface

modification as chemical and physical vapor deposition (CVD), (PVD), cathodic and magnetron sputtering, electroplating, electron beam, plasma and laser hardening, gas-flame, plasma and detonation thermal spraying, ion-plasma nitriding, etc. [3-11]. Of these methods, the lightest, cheapest, most affordable and most versatile is electrical spark deposition (ESD). The method has a number of advantages over the above methods [11-17], the main of which are: its simplicity, low cost of equipment, its easy technology, the insignificant heating of the layered products, absence of thermal deformations, low energy consumption and ease of

implementation of the technological operations, the possibility of hardening surfaces of complex shapes. The main disadvantages of this method is a small thickness, relatively higher roughness and unevenness of the applied coatings, and lower productivity. ESD can be used effectively to solve certain problems to improve the surface properties of titanium alloys. The ESD surface layer changes the friction conditions in two main directions: surface microgeometry change and change of surface composition and structure - a layer of high hardness and wear resistance can be created.

The study of the general laws and micro-mechanical properties of the formed layer and their influence on the mechanism and wear kinetics allows to determine ways for controlled management of the operational properties of the treated surfaces and to develop technological variants for ESD. This method is used for deposition of coatings on titanium and its alloys most often at a single pulse energy of 0.1-0.5 J [16-26], with a wide range of layering electrode materials - pure metals, alloys and carbide compositions.

All cited authors [11-26] report that with the increase of the energy of the pulses the thickness of the coatings increases, but parallel their roughness, the unevenness and the quantity of structural defects increase, which adversely affects their tribological characteristics. In order to obtain coatings with low roughness and fewer structural defects, it is necessary to use impulses with lower energy. In this case, however, the thickness of the coatings will have lower values. It is not known how this would affect the tribological properties of the coated surfaces.

In this regard, the present work is aimed at obtaining and studying wear-resistant coatings of hard alloys based on TiC, TiN, TiCN and TiB<sub>2</sub> by ESD with low pulse energy  $E=0.02-0.07$ J on the Ti-GR2 and on the widely popular titanium alloy Ti6Al4V. The solution of the set goal is achieved by performing the following tasks:

- studying the influence of low energy regimes on the roughness, thickness, microhardness and wear resistance of the obtained coatings;
- comparison of the parameters, properties and wear resistance of the coatings as a function of the pulse energy and the studied electrode materials in order to evaluate the possibilities

for their use for surface modification of titanium alloys and improving their negative tribological properties, and to expand the scope of their application;

- determination of suitable electrode materials and parameters of the ESD process to achieve improved hardness, wear resistance and service life of the coated titanium surface.

## 2. MATERIALS AND METHODS

It's known [11-13,15,19,21-26] that the wear resistance of coatings depends mainly on their roughness, thickness, composition, structure, and microhardness. In turn, these parameters depend on the modes and material of the electrodes for ESD. To establish a correlation between the wear characteristics and the parameters of the coatings in the present work the relationship: pulse energy and electrode material for ESD → topography, composition, structure and microhardness of the coatings → wear characteristics of the coated surfaces are considered and discussed.

“Carbide Hardedge” (England) apparatus is used with the following parameters: Short circuit current - 0.2-2.5 A, Voltage-  $U=80$  V, oscillation frequency of the vibrator - 100 Hz. The individual layering modes are numbered from 1 to 6 in the order of increase of pulse energy given in Table 1.

**Table 1.** Regimes for ESD whit vibrating electrode.

Nº of regimes,	1	2	3	4	5	6
Capacitance, $\mu$ F	1.5	3.5	5	7	10	20
Pulse energy $E \cdot 10^{-2}$ , J	0.5	1	1.6	2	3	7

The coatings are deposited on titanium alloy Ti6Al4V (GR5) and on technical titanium GR2 (Aisi UNS R R56200 and R50400) with electrodes with designations and composition according to Table 2.

**Table 2.** Composition of used ESD electrodes.

Type of ESD electrode	Chemical composition
TN	TiN+14%(Ni+Cr) + 1-2% (Cu-B-Al <sub>2</sub> O <sub>3</sub> -C)
TC-TN	TiC+TiN+14%(Cr+Ni+Mo+ 1-2% (Cu-B-Al <sub>2</sub> O <sub>3</sub> -C)
KNT16	TiCN + 23%(Ni+Mo)
TiB <sub>2</sub> -TiAl	74%Ti + 12%B + 14%Al [17-20]

The electrode materials listed in Table 2 can be divided into two categories - classic hardalloy electrode materials - TN, KNT16 and TC-TN [21-25]; and hard alloyed materials with nano structured additives - TiB<sub>2</sub>-TiAl -[17-20].

The surface roughness  $Ra$ ,  $\mu\text{m}$  and thickness  $\delta$ ,  $\mu\text{m}$  of the resulting coatings are measured by using profilometers -"Surtronic 3+", "TESA Rugosurf" 10-10G, and "AR-132B" at EN ISO 13565-2:1996 standards.

The microstructure and microhardness ( $HV$ ) of the coatings have been studied by optical microscopy on cross-sectional under indentation loads of 20g by metallographic microscopes Neophot 22. Microhardness of the layer, of the sub-layer (in depth to the base), and of the base itself has been measured.

The phase identification, the distribution of elements in the surface layer and microstructural analysis of the coatings along with the interface region were performed by an X-ray diffractometer Bruker D8 Advance in "Cu K $\alpha$ " radiation, by optical microscope, and an electron microscope "Bruker"; by scanning electron microscopy (SEM) "EVO MA10 Carl Zeiss".

The comparative friction tests were performed with tribotester type "Thumb-on-disk" under dry surface friction with hard-fixed abrasive particles in plane contact at the following conditions: load 4 N; nominal contact area  $2.25 \times 10^{-6} \text{m}^2$ ; nominal contact pressure  $17.4 \cdot 10^3 \text{N/m}^2$  disk rotation speed 60 rpm; sliding speed 0.239 m/s; type of abrasive surface - Corundum N<sup>o</sup> 1200, ambient temperature 22 °C. The test method consists of measuring the mass wear " $m$ " of the samples for a specific friction path " $L$ " (friction cycles) under load " $P$ " and glide speed " $V$ ". The mass wear is obtained as difference between the initial mass of the sample  $m_0$  and its mass  $m_i$  after a certain number of friction cycles:  $m = m_0 - m_i$ , mg. The mass of the samples before and after a given friction path is measured with an electronic balance WPS 180/C/2 to the nearest 0,1mg.

The following wear characteristics were calculated [27,28]:

- Wear intensity - the amount of wear per unit of friction work:  $I = \frac{m}{P \cdot L}$  mg/Nm, (1)

where  $m$  is the wear of the solid for the test time,  $P$  - the normal load,  $L$  - the friction path passed;

- Reduced wear intensity -  $i_r = \frac{m}{L}$ , mg/m; (2)

- Absolute abrasion resistance is the reciprocal of the reduced intensity -

$$I_r = \frac{1}{i_r} = \frac{L}{m}, \text{ m/mg}; \quad (3)$$

- The relative wear resistance -  $\Delta Ei$ , % which represents the ratio between the wear resistance of the worn coated sample and the wear resistance of the reference sample uncoated one in percent, and it is determined by the formula:

$$\Delta Ei = \frac{(I_{ri} - I_{re})}{I_{re}} \cdot 100, \%. \quad (4)$$

### 3. RESULTS AND DISCUSSION

#### 3.1. Topography, roughness, structure and microhardness of the coatings

The average values of the thickness  $\delta$ , of surface roughness  $Ra$ , of the  $Rk$  parameter - the height of the core of the roughness (DIN EN ISO 13565-1:1998-04, DIN EN ISO 13565-2:1998-04) and microhardness  $HV$  of coatings, obtained at two modes with average and maximum pulse energy for the "Carbide Hardedge" device - E=0.03 and 0.07] are shown in Table 3. Figs 1 and 2 display the change of the roughness parameters of the coatings  $Ra$ ,  $Rz$ ,  $Rt$  depending on the energy of the single pulses at the initial roughness of the titanium surface  $Ra=1.67 \mu\text{m}$ .

The data presented show that the resulting coatings have an acceptable for practical use density, uniformity, and repeatability of quality characteristics. Their roughness and thickness for the studied energy range vary in the range from  $Ra=2$  to  $3.5 \mu\text{m}$  and  $\delta$  - from 10 to  $15 \mu\text{m}$  (Table 3 and Figs. 1, 2). The results obtained show that the surface parameters of the coatings  $Rz$ ,  $Rmax$  are significantly higher than those of the original substrate (Fig. 2, Table 3), while the  $Ra$  parameter increases to a lesser extent. The parameter  $Rk$  (according to the international standard EN ISO 13565-2: 1996), which characterizes the wear of the surface in

the area of the coating, also increases significantly compared to that of the base (Table3). Higher  $Rk$  values can adversely affect wear resistance and reduce service life and lubrication retention index. It is established, that the specific values of the roughness and the thickness of the coatings are different for the different electrodes, but are similar. The lowest values of the roughness parameters were obtained at ESD with electrodes KNT16 and TN, and the highest - with electrodes  $TiB_2$ -TiAl. (Figs. 1, 2, Table 3), it can expect that they have greater coefficients of friction.

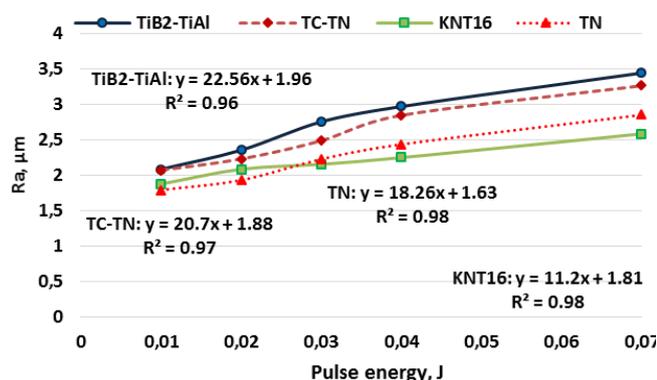


Fig. 1. Roughness  $Ra$  of coatings vs. the pulse energy at initial roughness of the base  $Ra=1.67 \mu m$ .

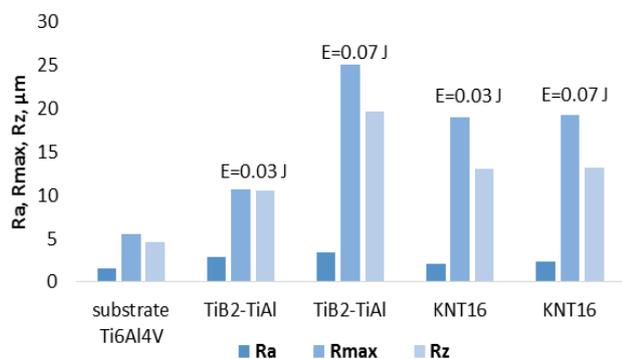


Fig. 2. Roughness parameters  $Ra$ ,  $Rz$ ,  $R_{max}$  of coatings vs the pulse energy at initial roughness of the base  $Ra=1.67 \mu m$ .

The increase in pulse energy results in a monotonic increase in the roughness and thickness of the coatings, and there is a proportional relationship between  $Ra$  and  $\delta$ , with the increase in thickness, the roughness grows and vice versa (Fig. 1,2 and Table 3). The results show that the coatings obtained at pulse energy up to 0.03J has values of roughness  $Ra$  in the range  $1.8 \div 3 \mu m$ , which are close to that of the initial titanium surface (Fig. 1). Therefore, the coatings obtained at a pulse energy of up to 0.03J can be used directly both

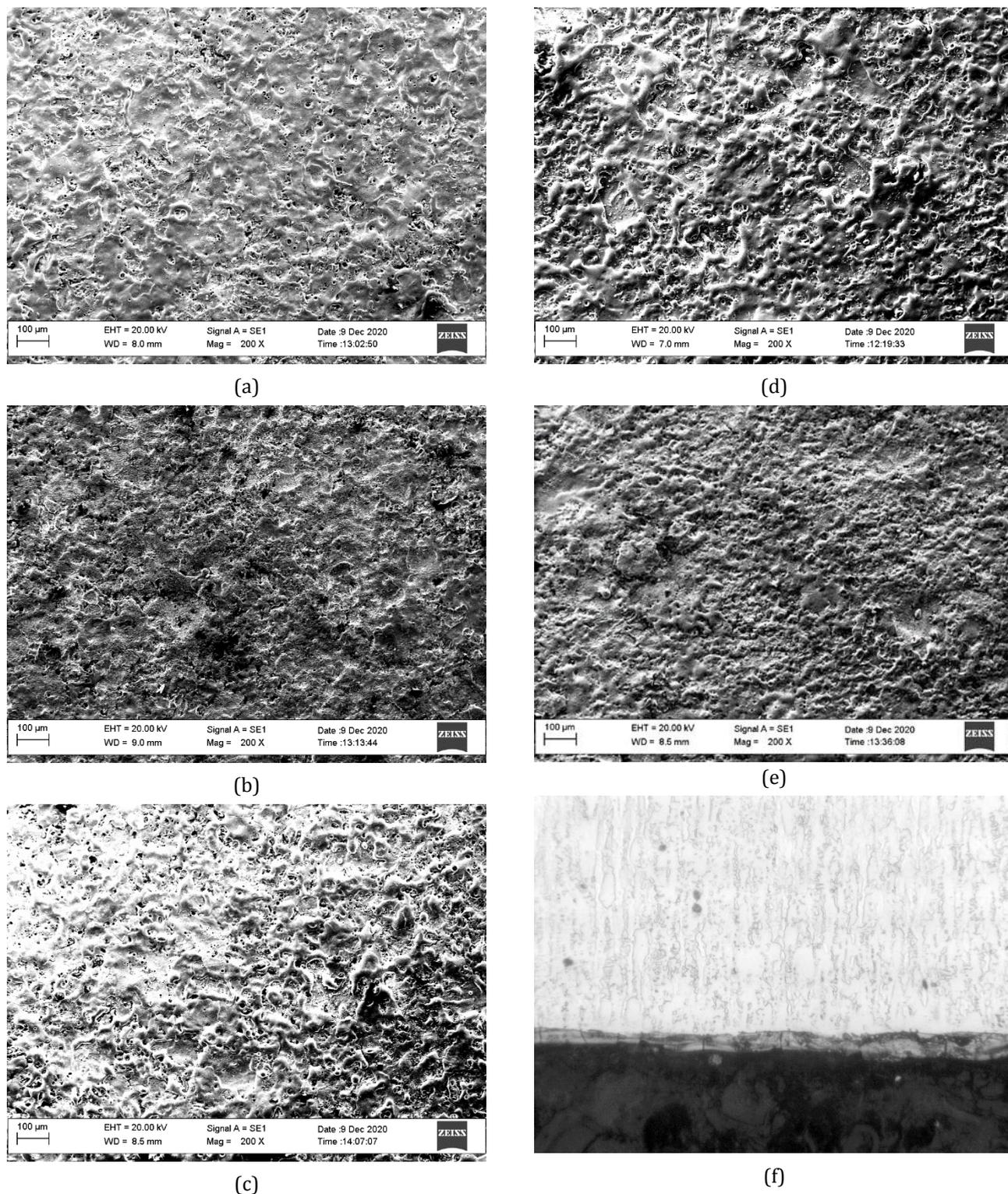
to increase the wear resistance of titanium alloys, and to smooth out unevenness and traces of previous treatment of the initial titanium surface, for example after additive technologies for the production of titanium parts or after rough and semi-finished mechanical or electroerosion treatments of titanium surfaces.

Table 3. Roughness  $Ra$ , thickness  $\delta$  and microhardness HV of coatings on titanium alloy Ti6Al4V.

Electrodes Designation	$E, J$	$Ra, \mu m$	$Rk, \mu m$	$\delta, \mu m$	$HV, GPa$
TN	0.03	2,3	8.22	10	9.85
TN	0.07	2,86	9.32	14	10.3
KNT16	0.03	2,16	6.86	12	10.4
KNT16	0.07	2,49	7.46	16	12.3
TC-TN	0.03	2,39	8.15	11	12.1
TC-TN	0.07	2,97	9.56	15	12.2
$TiB_2$ -TiAl	0.03	2,8	9.14	11	12.3
$TiB_2$ -TiAl	0.07	3,45	11.2	15	12.5
Ti6Al4V <sub>(base)</sub>	-	$1.67 \div 2.27$	$5.54 \div 6.94$	-	3.71

When the pulse energy rises above 0.04J, the roughness  $Ra$  of the coatings increases and assumes higher values than the initial one. The general appearance of the coating surfaces, are shown in Fig.3.

It can be seen that the surface of the coatings is formed mainly by melt. The photos show that at a pulse energy of 0.03 J, Fig.3a, the coatings from KNT16 electrode have a smaller structural components, without visible cracks and pores. The morphology of the coatings from the other studied electrodes is similar. At an energy of 0.07J - fig. 3 b,c,d,e however, individual protrusions can be observed as a result of transfer from a not completely molten solid phase, obtained due to the brittle destruction of the electrodes. Some microcracks and micro-irregularities of the surface are visible (Fig. 3 b,d,e). It is also observed the presence of a network of individual micropores, which are more characteristic of coatings from TC and TN electrodes than those of  $TiB_2$ -TiAl electrodes. In order to reduce and smooth micro-unevenness, and hence to improve the tribological characteristics of ESD coatings applied at a pulse energy above 0.04 J, additional surface treatment (smoothing, polishing etc.) may be recommended.



**Fig. 3.** Top view and cross-section of the coatings: (a), (b) - with electrode KNT16(TiCN+23%(Ni+Mo) -  $E=0.03$ J and  $E=0.07$ J]; (c) - with electrode TN(TiN+14%(Ni+Cr) +1-2%(Cu-B-Al<sub>2</sub>O<sub>3</sub>-C)- $E=0.07$ J]; (d) - with electrode TC-TN(TiC+TiN+14%(Ni+Mo)+1-2%(Cu-B-Al<sub>2</sub>O<sub>3</sub>-C) - $E=0.07$ J]; (e) - with electrode TiB<sub>2</sub>-TiAl - $E=0.07$ J]; (f) - cross-section of the KNT16 coating at  $E=0.03$ J].

The structure of the surface layer obtained with different electrodes under different modes is not significantly different. The structure consists of an upper layer - Fig. 3 f), and a substrate

material. Sublayer and transient heat affected zone, characteristic for vibrational methods at higher puls energy [12-14,16,22,26] are not registered.

The coatings have a microhardness varying within the range 9÷12.5GPa (Table 3), depending on the electrode material and pulse energy of the ESD process and is comparable to the data reported by [11,14-17,21,23]. Due to the structural inhomogeneity of the coatings and the presence of a matrix of lower hardness and hard carbide phases, the microhardness of the surface layers widely varies. The specific values from the individual measurements are in the range from 7 to 16 GPa. The values of the order of 16 GPa are reported for electrodes TC-TN, TiB<sub>2</sub>-TiAl and KNT16. The highest coefficient of increase of the microhardness - (3.3 times), has been observed at TiB<sub>2</sub>-TiAl electrodes, but the values of the same coefficient of coatings from KNT16 and TC-TN electrodes are very close. There is not established a clear dependence of *HV* on the ESD process parameters, but there is a tendency to increase with an increase in pulse energy. The results indicate that the ESD method and the coatings from tungsten-free electrodes significantly increase the microhardness of titanium alloys and can be effective for application on titanium alloys.

### 3.2. Phase composition of coatings

Fig. 4 shows the X-ray diffraction patterns of coatings deposited with TC-TN and TiB<sub>2</sub>-TiAl electrodes. The main phases registered in the coatings are given in Table 4. When TiC and TiN based electrodes have been used, the following main phases arranged according to the intensity of the characteristic lines have been registered in the coatings:  $\alpha$ -Ti, modified TiN<sub>0.3</sub>, TiN, TiC<sub>1-x</sub>, TiC<sub>x</sub>N<sub>y</sub>. Apparently, under the action of the spark discharges, TiC, TiN and TiCN partially decompose, forming separate low carbon and low nitrogen nitrides, carbides and carbonitrides, and on the other hand, Ti from the base reacts with the nitrogen and carbon from the atmosphere and the electrode, increasing the amount of TiN<sub>0.3</sub>. Presence of TiB, TiN<sub>0.3</sub> have been registered at ESD with TiB<sub>2</sub>-TiAl electrodes, also TiB<sub>2</sub> and TiAl<sub>3</sub>, but with a low intensity of peaks. Traces of TiC<sub>x</sub>N<sub>y</sub>, TiN, Al<sub>2</sub>O<sub>3</sub>, TiAl<sub>x</sub>N<sub>y</sub>, TiO<sub>2</sub>, TiO have been detected. The short contact time of the particles with the oxygen from the environment creates favorable conditions for reducing the oxidation of the coating, which is essential for wear resistance.

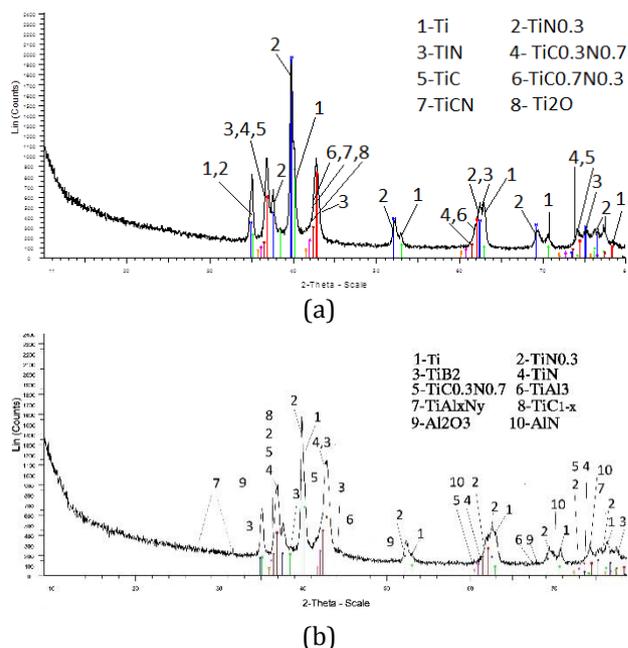
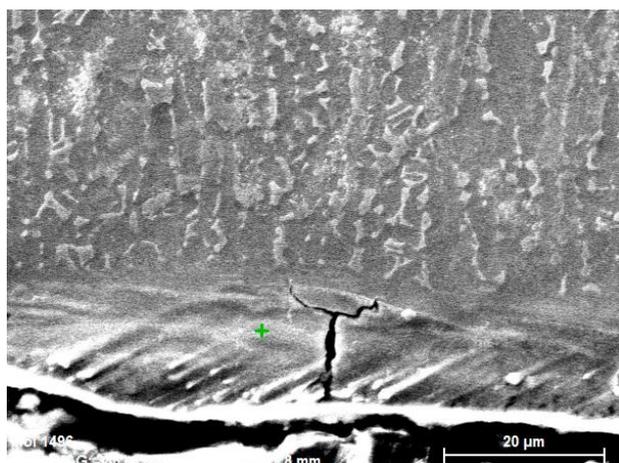


Fig. 4. X-ray diffraction patterns of KNT16 (a) and TiB<sub>2</sub>-TiAl, (b) coatings applied on Ti-GR2 alloys.

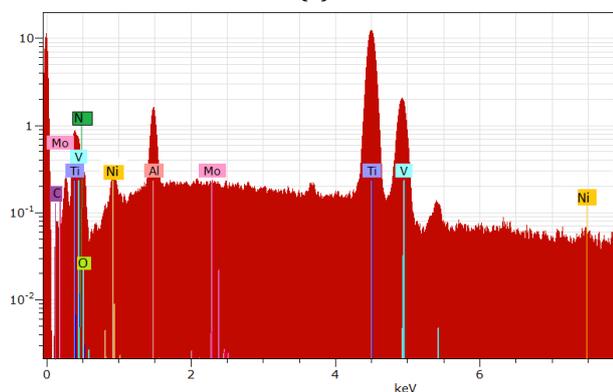
Table 4. Phase composition of coatings.

Phase/ Electrode	TC-TN	KNT16	TiB <sub>2</sub> -TiAl
	Average crystallite size, nm		
$\alpha$ -Ti	32	36	32
TiN <sub>0.3</sub>	36	31	33
TiN	13	12	-
TiC <sub>1-x</sub>	16	14	-
TiC <sub>x</sub> N <sub>y</sub>	10	6	traces
TiB	-	-	35
TiB <sub>2</sub>	-	-	21
TiAl <sub>3</sub>	-	-	26
TiAl <sub>x</sub> N <sub>y</sub>	-	-	traces
Al <sub>2</sub> O <sub>3</sub>	-	-	traces
TiO <sub>2</sub> ,TiO	traces	traces	traces

Fig. 5 shows a typical picture the elemental composition and microstructure of the coating of electrode KNT16 on Ti6Al4V alloys at E=0.03J. The elemental analysis (Fig. 5) showed the presence of Ti, Al, Mo, V, Ni, N,O and C in the layer surface. Based on the data obtained, it can be concluded that the elements, which are not involved in the formation of carbides, nitrides and borides form a solid solution with the substrate elements. The microrelief of the obtained coatings is uneven and heterogeneous in both structure and composition. The reverse diffusion of Ti from the substrate in direction of the coatings could be a reason for the observed picture.



(a)

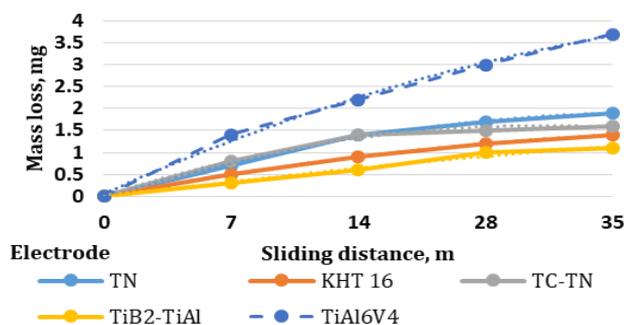


(b)

**Fig. 5** (a) Mapping of coating from KNT16 electrode, (b) EDX spectrum of coating from KNT16 electrode on Ti6Al4V alloys at  $E=0.03$  J.

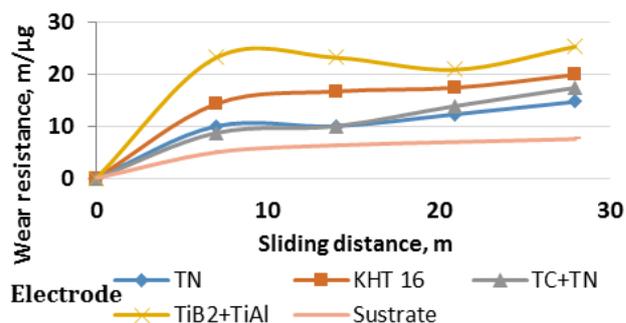
### 3.3. Coatings tribo tests results - Wear of coatings

The results of the comparative studies of the influence of pulse energy and electrode materials for ESD on the wear of the coatings are summarized in figs 6-9. The graphics dependences for the change of mass loss vs. the friction path are given in Fig. 6, and the wear resistance of the samples - in Fig. 7.



**Fig. 6.** Mass loss as a function of sliding distance at carbide electrode coatings on titanium alloy Ti6Al4V

The change in the wear rate, the wear intensity, the wear resistance and relative wear resistance of the coatings is similar.



**Fig. 7.** Wear resistance of Ti6Al4V alloy with ESD coatings from carbide electrodes applied at 0.03J.

In the study area, the mass loss is approximated for the substrate and the test coatings from the respective electrodes as following:

$$\text{Substrate: } -m=0.1x^2+1.5x-1.34, R^2=0.996 \quad (5)$$

$$\text{TN: } -m=0.1x^2+1.08x-1, R^2=1 \quad (6)$$

$$\text{TC-TN: } -m=0.05x^2+0.65x-0.6, R^2=0.997 \quad (7)$$

$$\text{KHT16: } -m=0.137x^2+1.2x-1.06, R^2=0.993 \quad (8)$$

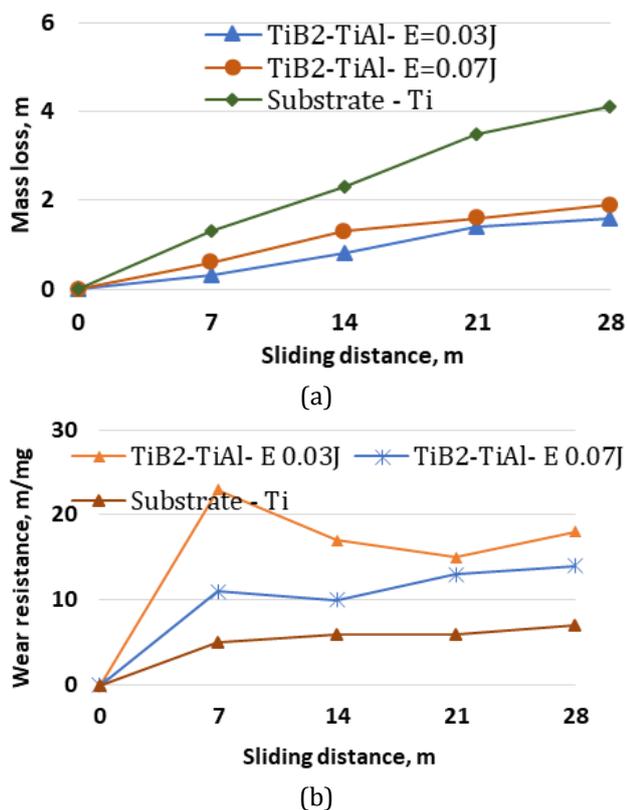
$$\text{TiB}_2\text{-TiAl: } -m=0.021x^2+0.419x-0.42, R^2=0.985 \quad (9)$$

From the obtained results, it is established that the mass wear of the coated samples is 2-4 times lower than that of the uncoated ones. Comparing the influence of the different electrode materials (Figs. 6, 7) it is found that at ESD with  $\text{TiB}_2\text{-TiAl}$  electrodes the wear of the samples is up to 1.2-1.4 times lower than that of similar materials based on TiC, TiN and TiCN. Apparently, the combination of  $\text{TiB}_2$  and TiAl and the presence of nanosized additives allow receiving higher wear resistance of the coated surfaces compared to that obtained with TiN, TiC and TiCN based electrodes. The fine-grained structure and nanosized additives of these coatings also contributes to the higher wear resistance. Of the tungsten-free electrodes, the coatings made of KNT16 electrode show the highest wear resistance. TiCN based electrodes obviously are more suitable for improving the wear resistance of titanium alloys than the mixture of TiC and TiN in the composition of the electrodes.

Surfaces, coated with TC-TN electrodes show higher wear resistance than those layered with TN electrodes, from which it can be concluded

that the presence of TiC in combination with TiN contributes to a greater extent to increase the wear resistance of coatings than only TiN, which is consistent with the results obtained in [24,25].

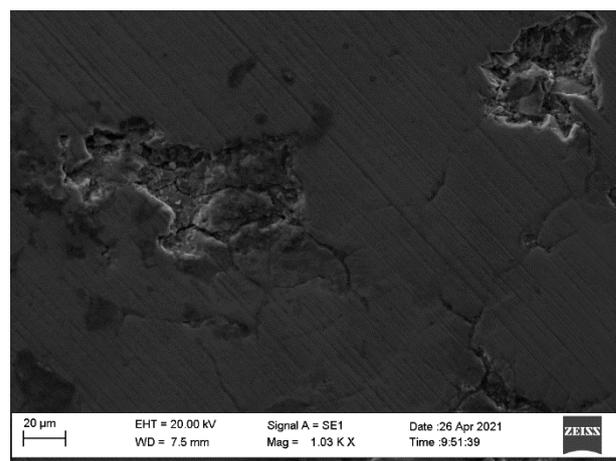
Fig. 8 shows the change in wear and wear resistance of the TiB<sub>2</sub>-TiAl electrode coatings applied at energies 0.03 and 0.07J vs sliding distance. Coatings deposited at an energy of 0.03 J show lower wear, although the thickness, amount of high-hard phases TiB, TiB<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, TiAl<sub>3</sub> and microhardness of the coatings obtained at a pulse energy of 0.07J are higher. Evidently, the higher values of roughness parameters at energy 0.07J adversely affect the wear resistance, but the deterioration is compensated to some extent by the greater thickness and the higher content of wear-resistant phases and this leads to relatively small differences in wear of the coatings, obtained at the two different energies.



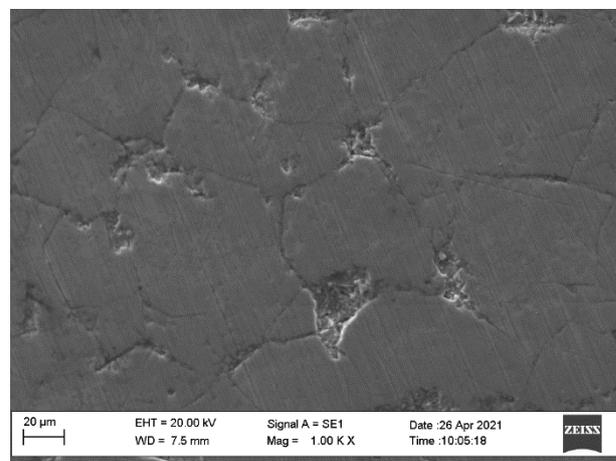
**Fig. 8.** Mass loss a) and wear resistance b) of coatings from TiB<sub>2</sub>-TiAl electrode on titanium alloy Ti-GR2.

Due to the lower roughness, better uniformity, finer structure, lower thermal impact on the substrate, coatings obtained at ESD with the lower pulse energy show higher wear resistance, moreover, they are more suitable and for layering of parts with high requirements for accuracy and surface quality.

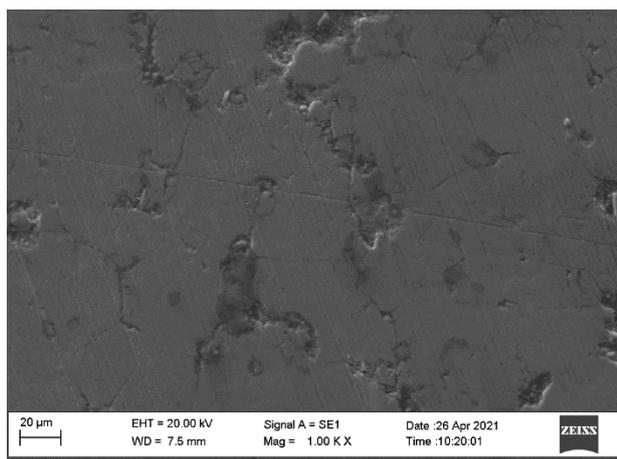
Figure 9 shows micrographs of uncoated and coated worn surfaces. The micrographs show that on the uncoated surface -Fig.9a) there are traces (scratches) of abrasive and relatively deep craters from adhesion wear. The debris is in the form of chipped or ripped particles with a rounded shape. After less than 14 m of friction, the uncoated specimens are already deeply worn. The wear of the layered specimens after a friction path of 28 m is similar, but the amount and the depth of the scratches and craters are significantly smaller than those of the uncoated ones at a friction path of 14 m. In both uncoated and coated specimens, the presence of a network of microcracks is registered, from which the development and growth of the craters from the adhesion wear begins. While in the uncoated specimens, at a friction path between 7 and 14 m, relatively deep craters and scratches are already present, in the layered ones the appearance of the same begins after the 20<sup>th</sup> meter. Therefore, ESD slows down and reduces the development of the scratches and craters over the time.



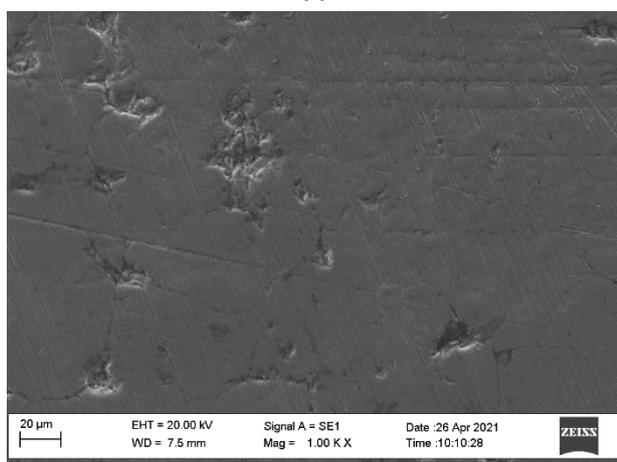
(a)



(b)



(c)



(d)

**Fig. 9.** Micrographs of uncoated Ti-GR2 and coated at pulse energy  $E=0.03$ J worn surfaces at a friction path 28 m; (a) - uncoated Ti GR2, (b) - with electrode KNT16, (c) - with electrode TC-TN, (d) - with electrode  $TiB_2-TiAl$ .

The results obtained show that the influence of the electrode material is also related to the ESD mode. The increase of the pulse energy up to 0.03J as a result increases the durability of the coated surface. However, with a further increase in energy, due to the higher roughness and unevenness of the coatings, the wear resistance gradually begins to decrease. However, the above conclusion is not valid for the coatings of KNT16 electrode, where with increasing energy to 0.07J the wear resistance also increases due to the lower roughness parameters of the surfaces coated with this electrode.

The results of the present studies show that all obtained coatings applied by non-tungsten electrodes at low pulse energy reduce the wear and slow it down over the time. The lowest wear, respectively the highest wear resistance show the coatings from  $TiB_2-TiAl$  electrodes at a pulse energy of 0.03 J and from KNT16 at 0.07 J pulse energy.

#### 4. CONCLUSIONS

The influence the low pulse energy at ESD process on the qualitative characteristics and the wear of coatings obtained from electrodes based of TiC, TiN, TiCN and  $TiB_2-TiAl$  on titanium alloys was investigated.

Coatings with a thickness 10 to 15  $\mu m$ , roughness  $Ra$ - 2 - to 3.5  $\mu m$ , microhardness to 12.5 GPa and wear resistance over 2-4 times higher than that of the uncoated surfaces have been obtained using a low-energy ESD process. All resulting coatings reduce the intensity of wear, slow its development over time and can be effectively used to increase the durability of titanium surfaces in many new industrial applications.

The conditions and process parameters for ESD, at which has been obtained the lowest wear of coated surfaces have been determined. The most promising in terms of the properties of the coatings are the  $TiB_2-TiAl$  and KNT16 electrodes. The increase in the wear resistance of the coated surfaces with electrode  $TiB_2-TiAl$  is up to 4 times larger than the uncoateds and 1.2-1.4 times higher than when using the TiC and TiN based electrodes.

The obtained equations for the dependence of the roughness  $Ra$  and the wear on the used energy allow us to choose with sufficient accuracy the mode of ESD for the used electrode depending on the desired roughness and wear resistance of the layered surface.

The results obtained in this paper show that non-tungsten carbide electrodes can be effectively used for low pulse energy ESDs to improve the surface properties of titanium alloys and allow the use of these excellent materials in many new industrial applications.

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