Electrospark alloying for deposition on aluminum surface of Al-Sn coatings and their wear resistance under dry friction

V. I. Agafii[a], V. I. Petrenko[a], V. M. Fomichev[b], V. I. Yurchenko[b], E. V. Yurchenko[b], A. I. Dikusar[a,b]

[a]Institute of Applied Physics, Academy of Sciences of Moldova,
5, Academiei str., Chisinau, MD-2028, Republic of Moldova
[b]Shevchenko Pridnestrov'e State University,
128, 25 Oktyabrya str., Tiraspol, Republic of Moldova,
e-mail: dikusar@phys.asm.md

Some aspects of coating deposition on aluminum substrate by electrospark alloying with tool-electrode from Al-Sn alloy stimulating the SnO_2 nanofibers formation in coatings have been studied. Wear resistance of such coatings, under dry friction conditions, in conjunction with a counterbody from hardened steel has been investigated. The conditions under which the coatings thus obtained manifest the of effect of the maximal wear excessof the counterbody compared to the wear of the coatings containing SnO_2 nanofibers have been specified. The effect reaches its maximum value under the dry friction after the treatment of the surface in the mode of "sparking" at a constant energy supply in the spark gap: at high rates of the tool electrode movement with respect to the specimen and at relatively large times of the electrospark effect on the treated surface.

Keywords: electrospark alloying, Al-Sn alloy, nanofiber, wear-resistance.

УДК 621.9.047.7

INTRODUCTION

During the study of properties of coatings on the aluminum alloy D1 surface that were manufactured using the electrodischarge treatment – electrospark alloying (ESA) – with Al-Sn electrodes, the excessive wear of the counterbody in the tribological testing process under conditions of friction in the presence of a lubricant was detected [1, 2]. In certain cases during those testings the wear of the coating was less by an order of magnitude than the wear of the counterbody made of the hardened steel tool but at the same time an average microhardness of a coating does not exceed the microhardness of the substrate metal. The effect of the abnormal wear, as shown in [2], is due to the appearance of the tin dioxide nanofibers of high hardness on the surface layers of the aluminum alloy. Hardness of SnO_2 macroscopic specimens is in the range of 1000–1200 kg/mm^2 [3]. However, since tin dioxide fibers formed during the ESA are extremely small, their properties as well as properties of the formed alloy can differ from those of a bulk material.

The studies of properties of such coatings [1, 2, 4] were carried out on samples manufactured by means of ALIER-31 facility (SCINTI, Moldova) for the electrospark alloying, with the coatings being plated manually at various operation parameters. It is evident that the composition of the manufactured coatings, as well as their properties, should substantially depend on the conditions of interaction between the tool electrode (TE) and the workpiece surface, since these conditions determine the controllability of the treatment parameters. However, during the manual coating process such conditions seem hard to be maintained because the parameters such as the TE feed rate across the treated surface and the force of the TE pressing to the workpiece surface are set by an operator, hence, they can significantly vary, i.e. actually be uncontrollable.

This work considers manufacturing of electrospark coatings on aluminum alloys at a higher level of controlling the parameters of the process as well as properties of the obtained coatings. The control of the parameters was carried out by automation of the coating process and stabilization of the TE feed rate across the workpiece surface. Parameters of the transverse vibration which ensured the width of the manufactured coating layer were also established. The rate of the coating process, roughness, elemental composition and morphology of the layers manufactured, as well as their wear resistance during dry friction, were investigated. The necessity of studying the wear resistance under the dry friction conditions was determined by a possibility to use such materials as an abrasive.

EXPERIMENTAL

The 8-mm-diameter Al-Sn rods were used as the TE. They were doped with Cu (~ 1 wt %) and Ti (~ 1 wt %).

The alloy of the required chemical composition was melted in a graphite crucible with the use of inductor of a high frequency – VChI10U device. The melt was poured then into a specially made metal mold to obtain ø8x50 mm rod that served as the TE. The production technology consisted of a few operations, namely: a) fusion mixture preparation; b) melting in an induction furnace; c) pouring the melted alloy into a metal mold and d) cutting of shrinker, clearing, turning.

To obtain an alloy of a preset composition pure aluminum and tin were used. Doping components were introduced as intermediate alloys (50% Al + + 50% Cu) and (90% Al + 10% Ti). Mixture calculation was carried out for the average content of elements (wt %): Sn –20; Cu–1; Ti–0.1; and the balance Al.

The sheets from D1 aluminum alloy (GOST 4784) were used for the substrate. Specimens of a special form were made of the sheets by cutting.

An ALIER-31 installation served as the power source for the electrospark plating. A peculiarity of this device is that the frequency of the generated pulses is not directly connected with the vibration frequency of the TE but is set independently. The frequency depends on the energy in a pulse. The parameters of technological pulses of the generator of an ALIER-31 installation are listed in Table 1. The operation mode 5 of that installation was used in the present study. The frequency of the preset pulses was ~ 0.1 kHz. This was reached using a special regulator of frequency (the energy coefficient).

Table 1. Parameters of technological pulses of the generator of ALIER-31

Mode	Pulse duration, μs (± 10%)	Amplitude of current pulse, A (± 20%)	Pulse energy, J
1	16	125	0.036
2	31	125	007
3	62	175	0.2
4	125	175	0.39
5	250	175	0.79
6	500	175	1.58
7	1000	175	3.15

In order to produce nanofiber structures under controllable conditions of electrospark plating and determine the optimal modes, an experimental facility was developed for a mechanized coating with a wide range of parameters (Fig. 1). Standard vibrogenerator *2* of ALIER-31 was fixed on a vertical milling head of a milling machine so that it could perform oscillating movements with the adjustable amplitude and frequency in the direction perpendicular to the movement of sliding carriage *5* on which sample *4* was fastened with screws. The amplitude was regulated by means of a special drive cam mounted on a vertical shaft of the machine with a possibility of adjusting it in the range of 1 to 10 mm. This made it possible to produce a track of coatings of different widths on the specimen. The frequency of the transverse oscillations was ensured by the rotation speed (from 20 to 150 rot/min) of the vertical shaft. Direct current engine *6* was used as the drive of the shaft.

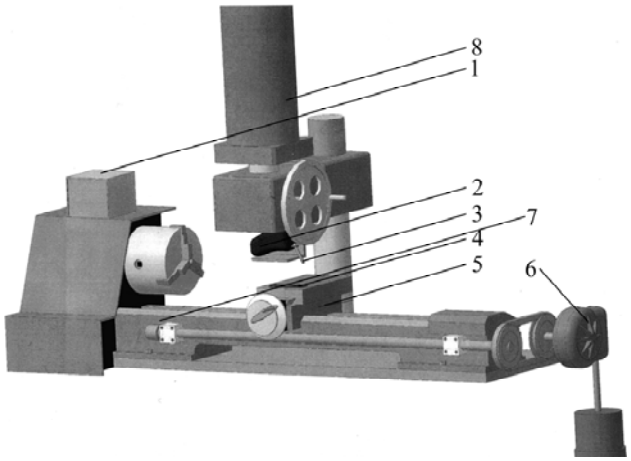


Fig. 1. Scheme of ESA experimental facility for the mechanized coating. 1 – ALIER-31; 2 – vibrogenerator; 3 – electrode; 4 – specimen; 5 – sliding carriage; 6 – regulated drive of sliding carriage; 7 – installation bed; 8 – regulated drive of transversal vibrator.

Fig. 2. Specimens for the coating. On the right - metal block blank for specimen, on the left - specimen ready for ESA.

Specimen *4* was fixed by screws on horizontal sliding carriage *5* of the facility. A special drive *6* (a constant current electric engine plus a reducer) was used to move it along the guide ways. Such device allowed plating of some layers step-by-step during every forward and backward movement of the carriage. The adjustable power supply allowed controlling the drive speed. Due to this device configuration the TE fixed on vibrogenerator moves relative to the specimen with a constant preset feed rate. The feed movement of the sliding carriage was regulated in the range of 0.2–6.0 mm/s.

In addition to the indicated mechanical parameters (the specimen feed rate, amplitude and frequency of the transverse oscillations of the vibrator), the ALIER-31 installation itself made it possible to vary

the mode of operation, the energy coefficient and amplitude of the electrode vibration.

Thus the experimental facility provided an opportunity to vary modes by 6 parameters during the mechanized (hence, with stabilized parameters) coating process.

The methods for direct coating deposition were as follows. For the specimens, alloy D1 (GOST 4784) was used as the substrate. The specimens in a rectangular form (Fig. 2) were cut from D1 alloy sheets for friction and wear tests.

After the milling cut the specimens surfaces were polished with an abrasive cloth strips to diminish roughness before the ESA coating. After polishing and marking the specimens were weighed on a VLR 200 analytic balance, and afterwards they were fixed with two screws on the sliding carriage of the experimental facility. The electrode from the Al-Sn alloy (~ 20 mass % of Sn, manufactured by the above method) was also preliminary weighted and fastened in the vibration generator of ALIER-31.

The required operation modes were displayed on the control panel of the experimental facility, i.e., the energy coefficient, amplitude of the generator, mode of operation, and the amplitude and frequency of the transverse oscillations. When the facility was switched, on the mechanized coating the process started due to the sliding carriage reciprocal movement. After plating one or two layers, the specimens and electrodes were weighed again to determine the material gain or loss of the specimen or the electrode.

Two methods of coating deposition were used. According to method *1*, a constant number of coated layers at every preset speed of the TE movement relative to the specimen was deposited (at this case the effective time of coating deposition depends on the feed rate). Method *2* presupposes the usage of a constant value of the "supplied charge" or an amount of energy introduced into the discharge gap during the deposition process (in the present study it is refered to as the method "with constant energy amount"). Using method *2*, the number of the plated coatings was increased proportionally to an increase in the TE feed rate. According to method *1*, the constant number of the deposited layers was *4* at various TE feed rates with respect to the specimen; the rates varied in the range of 0.3–2 mm/s: the TE traveled as many as four times with a preset rate along the entire surface under treatment (Fig. 2). In the case of deposition by method *2* four layers were deposited (the TE traveled *4* times along the surface) at the speed of 0.5 mm/s of the TE displacement and 16 layers at the feed rate of 2 mm/s; 8 and 12 layers were deposited at the feed rates of 1 and 1.5 mm/ s, respectively.

The results of the weighting were used to determine a specific deposition rate G in mg/(s·cm^2) which, depending on conditions, could be either of a positive or of a negative value; in the latter case, the weight of the specimen after the treatment did not increase but rather decreased. The total time of the treatment and the overall area of the modified surface were taken into account to calculate G.

The surfaces of the specimens (prior to and after the treatment) were also examined in order to study the morphology and the elemental composition using the scanning electron microscopy − a TESCAN scanning microscope with an INCA Energy EDX (Oxford, Great Britain) attachment for the surface elemental analysis.

To determine the surfaces roughness of the specimens (parameter Ra) and their profiles a Surtonic profilograph-pofilometer (Taylor Hobson, GB) was used. The measurements were performed at 12 points along the preset length of tracing of 12.5 mm. The average value of Ra and a standard deviation were calculated based on the obtained measurements.

The wear tests were carried out using a friction machine with a reciprocal movement (from the Institute of Applied Physics of the Academy of Sciences of Moldova [2, 5]).

The rectangular 3 x 25 x 30 mm specimens from hardened steel with a microhardness of 650 ± 50 kG/mm^2 were used as the counterbodies. A counterbody was mounted perpendicular to the surface of the tested specimen. The area of the counterbody contacted with the tested surface was 9 mm^2. The working area length contacting the counterbody was 48 mm. The frequency of sliding of the counterbody against the specimen (a reciprocal movement) was 45 double strokes per minute.

The tests were performed at a constant load of 2 kG for 5 hours. The specimen and the counterbody were weighted every hour during the testing (with the latter being interrupted), and the surface roughness was measured after every 1, 3 and 5 h of the experiment.

The testing technique used allowed not only to study the dependence of an absolute wear of the counterbody surface and the treated surface on the parameters of the treatment, but also to determine the effect of roughness on the wear-induced material loss that was registered, and to study the relative characteristics, one being K value that equals the ratio of the counterbody absolute wear (in mg) to the wear of the surface treated using the ESA. In addition, that technique can be used to study the dynamics of the wear characteristics of both the specimen and the counterbody, as well as the dependence of value K on the time of testing. It seems obvious that since the surface roughness varied in the testing pro-

cess, the absolute values of wear could also vary with time. During the treatment, the removal of the material from the surface occurred, hence, the change in the wear characteristics with time was indicative of the properties of deeper layers of the coating.

In certain experiments it was not the loss of weight of the specimen under treatment that was detected but the weight increase. The weight loss of the counterbody was observed in all cases. It is clear that in such cases K value was accepted to equal ∞.

RESULTS AND DISCUSSION

The Deposition Rate and the Composition of the Surface Layer

Figure 3 shows the dependences of the mass changes in aluminum specimens. Figure 4 demonstrates the dependences of a specific deposition rate on the TE feed rate across the surface under treatment. It is seen that regardless of the spread in the experimental data and basically different methods of treatment (with a constant number of layers – method *1*, and with constant energy amount – method *2*), a specific deposition rate remains to be constant in a certain interval of the TE feed rates. It is ~ 0.03 mg/(s·cm^2) at low TE feed rates and ~ – 0.02 mg/(s·cm^2) at higher rates. A transition from method *1* to method *2* of the treatment changes only the "critical" value of the TE feed rate, when we can notice the transition from the ESA mode which yields the weight gain of the specimen under treatment (let us call it mode I) to the mode where the mass loss occurs after the ESA (we shall refer to it as the mode of "sparking" or mode II, which means modification of the surface under sparks action without noticeable weight gain), Fig. 4.

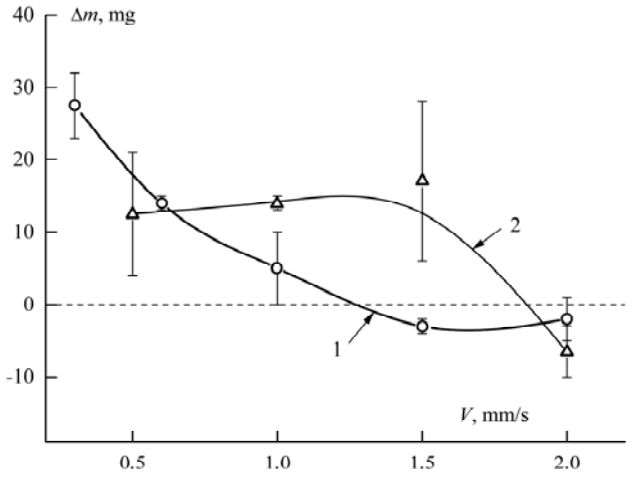


Fig. 3. Dependence of mass gain Δm on TE feed rate after ESA deposition with constant number of coated layers (1) and with constant energy amount (2).

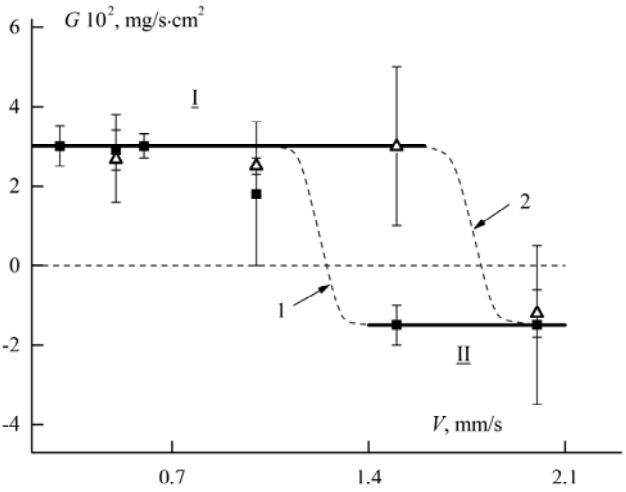


Fig. 4. Dependence of ESA deposition rate on TE feed rate for specimens obtained by method 1 (constant number of layers) and method 2 (constant amount of energy). Here: region I – mode with mass gain; region II – mode with mass loss.

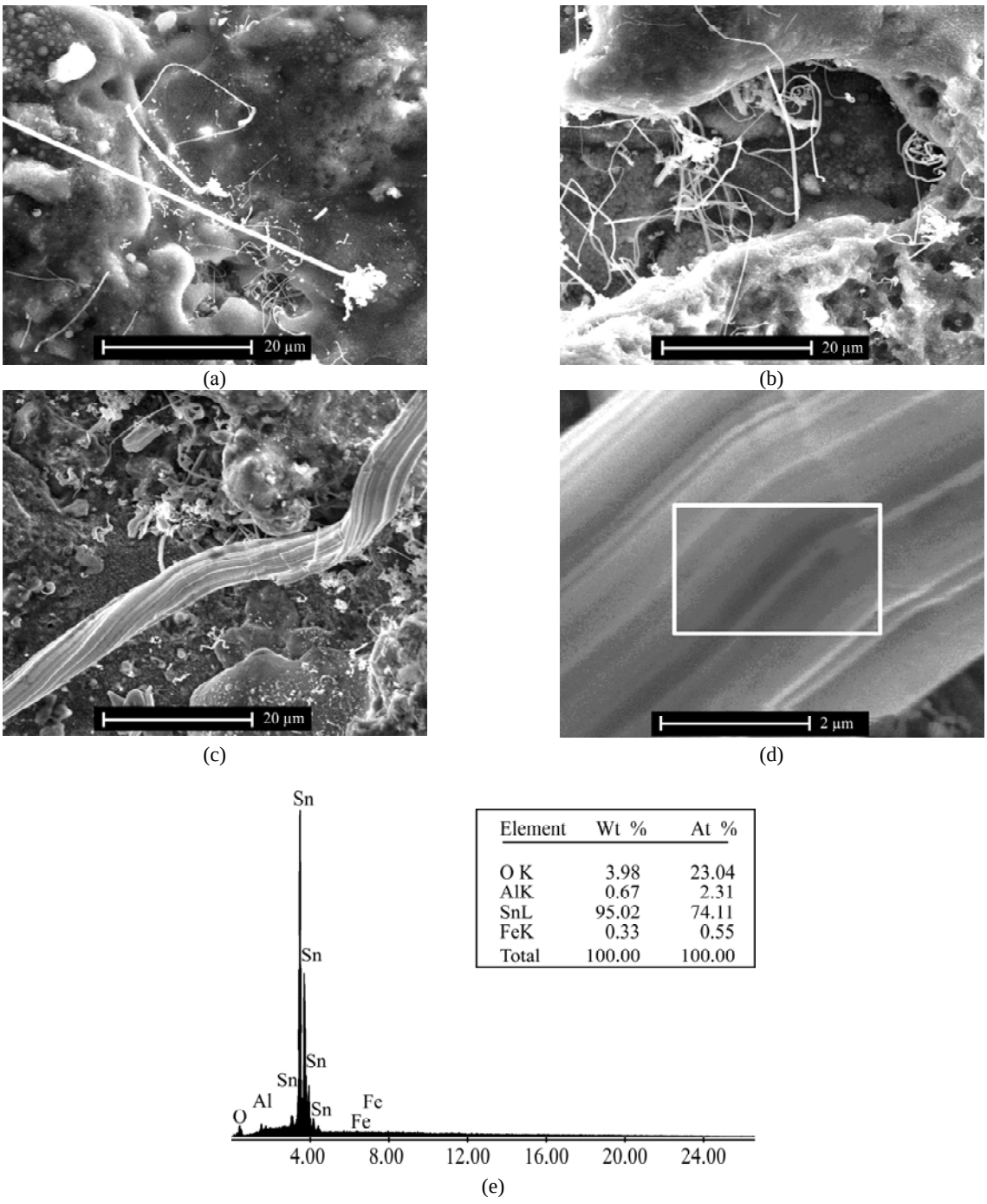
It was demonstrated that nanofibers are formed in the surface layer during the ESA process in the manual mode [1, 2, 4]. The nanofibers composition is similar to that of the tin oxide. Fig. 5 shows that nanofibers are also formed during the automatic coating process. In certain cases they are even of micrometric sizes (Figs. 5c,d). However, in this case (the formation of "thick" fibers) it is possible to determine their elemental composition more precisely (Fig. 5e). It is obvious that the stoichiometry of the fiber is such that tin concentration is substantially higher than that corresponding to SnO_2. The evident reason for this phenomenon is pulling the tin fibers with an oxidized surface out of the tin alloy melt under the action of an electric discharge. The fiber core is tin. It is apparent that the ratio of tin and the surface oxide in the fiber will depend on both the size of the melted drop (i.e., the diameter of the forming fiber) and the modes of the electric treatment including the TE feed rate across the specimen. The change of the elemental composition of nano(micro)fibers should lead to the change of the surface properties.

The elemental analysis of the total surface shows that the surface layer consists of the mixture of aluminum and tin oxides with different content of these elements, which depends on the modes of treatment.

Roughness of the Surface after the ESA

One main peculiarity of the ESA is a very high roughness of the surface. As is seen from Fig. 6, it depends strongly on the TE feed rate across the specimen.

The highest roughness is observed at low TE feed rates. The interval values of Ra in Fig. 6 show the roughness change of a few specimens but not the



Element	Wt %	At %
O K	3.98	23.04
AlK	0.67	2.31
SnL	95.02	74.11
FeK	0.33	0.55
Total	100.00	100.00

Fig. 5. Morphology of surface layers manufactured using method *1* at TE feed rate of 0.6 mm/s (a, b), 1 mm/s (c, d), EDX spectrum and elemental composition of the surface segment (e) marked in Fig. 5d.

roughness variation on the surface of the single one. Thus, e.g., if for the surfaces manufactured at V = 0.3 mm/s, a standard deviation for Ra at different points on a single specimen was from 3 to 6% of the measured value, for different specimens the deviation from the average values of Ra was up to 40% (Fig. 6). This again emphasizes (along with the data in Fig. 4) that the ESA is a process which is hard to control from the quantitative viewpoint. However, in spite of the spread in the experimental data, the treatment using different methods yields close results as to the roughness.

In a wide range of the TE feed rates there are similar values of Ra for the both methods *1* and *2* (Fig. 6). Exceptions are in the experiments with the specimens obtained by method *2* in the "sparking" mode (the experiments at V = 2 mm/s) (Fig. 6, 7).

Wear Tests of the Surfaces Treated using Method 1 (Constant Number of Deposited Layers)

The results of the wear tests showed that the value of K (provided that the treatment is performed in mode *1* at a building-up of coatings) can indeed exceed the unity (the rate of wear of the treated surface

was 2–3-fold less that the rate of the counterbody wear, as given in Fig. 8). However, after 1 hour testing, the counterbody wear could exceed the wear of the treated surface almost by an order of magnitude (Fig. 8).

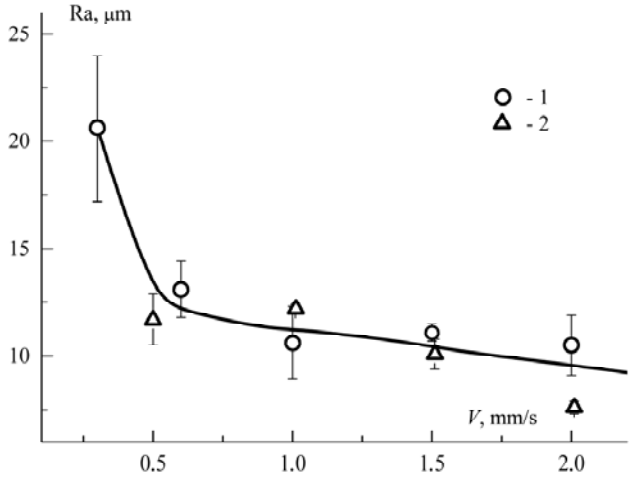


Fig. 6. Dependence of surface roughness (Ra) on TE feed rate after deposition using different ESA methods: 1 – with constant number of deposited layers (method *1*) and 2 – with constant energy amount (method *2*).

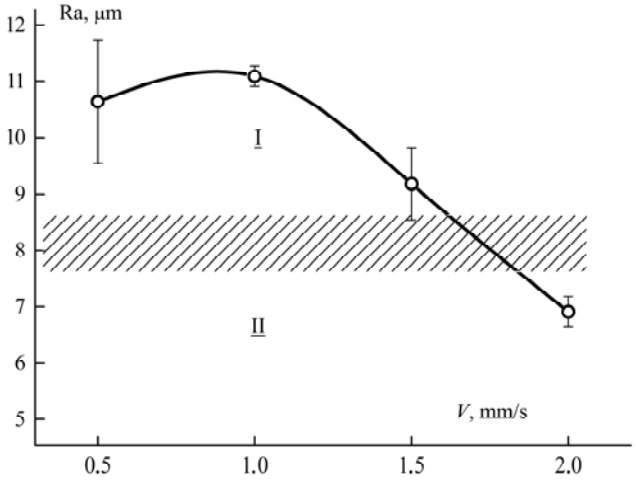


Fig. 7. Ra dependence on TE feed rate for method *2* treatment. Dashed area is region of transition from mode I to "sparking" mode (mode II).

This effect was not observed at higher values of *V*. The critical value, at which the transition of the relative wear from the values of $K > 1$ to $K < 1$ occurred at the values of *V* when the "sparking" mode was observed (Fig. 4). It took place when the rate of the counterbody wear was substantially lower than the rate of the surface wear,

Wear Resistance Tests of Surfaces Treated Using Method 2 (with Constant Energy Amount Induced in the Spark Gap During the Process).

As is follows from Fig. 9, the excessive wear of the counterbody relatively to the treated surfaces is observed for the specimens obtained by method *2* in all cases. For the surfaces manufactured in the "sparking" mode the *K* value is maximal, and the counterbody wear exceeds the wear of the ESA surface almost by an order of magnitude.

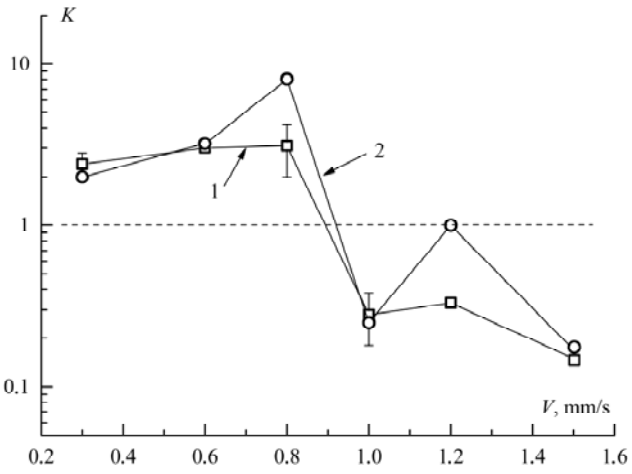


Fig. 8. Dependence of relative wear rate of hard steel counterbody on TE feed rate after 5 h (1) and 1 h (2) of testing.

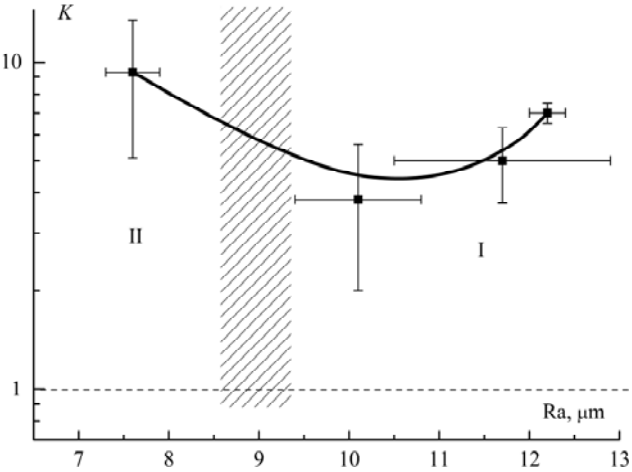


Fig. 9. Dependence of counterbody relative wear on surface roughness obtained after ESA for surfaces treated under condition of constant energy supply into discharge gap during treatment. Here: I and II – modes (as in Fig. 4,).

The comparison of the results in Figs. 4, 8 and 9 shows that treatment under mode II is accompanied against: 1) the weight loss after the treatment for both the specimen and the TE; 2) the decrease in the surface roughness; 3) reaching maximum values of *K*. Table 2 lists the time values, the absolute wear values and *K* values. It is clear that at the initial periods of the wear testing, *K* values can reach the magnitudes which substantially exceed *K* values that were obtained after 5 hours of testing. Here, the surface roughness: 1) is minimal as compared to that of the surfaces produced using all other variants of treatment; 2) slightly changes during the wear testing (Table 2).

In a number of the experiments, as it follows from the results presented in Table 2, the mass of the specimens after testing is found to increase, which testifies to the fact that the material of the counterbody (hardened steel) just remains on the ESA trea-

Table 2. Results of wear testing of the aluminum alloy specimens treated with Al-Sn TE at TE feed rate V = 2 mm/s (16 passes of the sliding carriuage along the specimen)

Number	Specimen weight gain after ESA Δm, mg	Initial Ra, μm	Duration of testing, h	Ra, μm	Specimen wear $\Delta m^{sp.}$, mg	Counterbody wear, Δm^{cb}, mg	$K = \Delta m^{cb}/\Delta m^{sp.}$
1	– 10	7.9±0.7	1	7.4±0.8	0.05	0.85	17
			2		0	0.40	25
			3	7.3±0.6	0	0.15	28
			4		0.1	0.05	9.7
			5	7.5±0.6	0.1	0.05	5
			Σ		0.25	1.50	
2	– 3	7.2±0.7	1	6.1±1.0	0.10	0.70	7
			2		+0.10	0.15	∞
			3	5.9±0.8	+0.15	0.30	∞
			4		0.10	0.10	∞
			5	6.0±1.0	0.15	0.10	13.5
			Σ		0.10	1.35	

ted surface during the friction process. This is observed during the surface treatment of aluminum alloy using the TE from Al-Sn in the "sparking" mode. As it follows from Fig. 9, the maximal value of K is registered, whereas the roughness of the surface is minimal. However, during the treatment in the mode of a weight-gain of the surface layer, K increase occurs during the growth of roughness of the surface after treatment (Fig. 9).

CONCLUSIONS

The analysis of the results obtained through the present investigation makes it possible to infer that two different modes of treatment are possible using the ESA treatment of the aluminum alloy surface with the TE made from Al-Sn alloy. The first, observed at relatively low TE feed rates across the treated surface, is characterized by the weight gain of the surface under treatment at a constant specific deposition rate (in relation to a unit of the area being treated). For the second variant (at relatively high TE feed rates), modification of the surface is registered accompanied by the loss in weight of the treated workpiece (also at a constant specific rate). The use of two different methods of treatment (with a constant number of layers (number of the TE sliding movements across the surface) and a constant value of energy supply in the discharge gap during the treatment, showed that both of the above modes (with the gain and loss in weight) are observed in the two methods under study. The only difference is that under the condition of a constant energy supply, the transition to the loss-weight mode (a "sparking" mode) occurs at higher TE feed rates across the workpiece.

It has been shown that a substantial excess in the wear of the counterbody made from hard steel compared to the wear of the surface from the aluminum alloy treated with Al-Sn TE, which resulted from the presence of SnO_2 fibers in the deposited coating, is observed under conditions of dry friction after different modes and methods of treatment (earlier it was found to occur during the lubricated friction [1–3]). However, this excess of the counterbody wear reaches its maximal value after the surface treatment in the "sparking" mode and at a constant energy supply in the discharge gap (at high TE feed rates across the specimen and relatively long times of electrospark effect on the treated surface).

The results that have been obtained in the present study can be used as a basis for manufacturing renewed highly efficient abrasive surfaces.

ACKNOWLEGMENTS

This work was supported in part by the Academy of Sciences of Moldova (project no. 11.817.05.05A "Electro-physicochemical Methods for Manufacturing and Treatment of New Materials and Coatings with Improved Functional Properties"), and in part by the Pridnestrov'e Shevchenko State University.

REFERENCES

1. Dikusar A. Obtaining Nanowires under Conditions of Electrodischarge Treatment. *Nanowires – Implementations and Applications.* Abbas Hashim, Ed., Intech. Org., 2011. pp. 357–374.
2. Agafii V.I., Urchenko V.A., Yurchenko V.I., Fomichev V.M., Petrenko V.I., and Dikusar A.I. Wear Resistance of Coatings Manufactured by Electric Spark Plating with Al-Sn Electrodes. *Surf. Eng. Appl. Electrochem*. 2011, **47**(6), 488–492.

3. Lebedeva S.I., *Opredelenie mikrotverdosti mineralov* (Determination of Microhardness of Minerals), Moscow, 1964.
4. Yurchenko V.I., Yurchenko E.V., Fomichev V.M., Baranov S.A. and Dikusar A.I., Obtaining of Nanowires in Conditions of Electrodischarge Treatment with Al-Sn Alloy. *Surf. Eng. Appl. Electrochem*. 2009, **45**(4), 259–264.
5. Agafii V., Parshutin V. Mashina treniya (Machine of Friction), Patent MD 2966 C2 2006. 01. 31. DOPI nr. 1/2006.

Received 18.09.12
Accepted 12.12.12

Реферат

Исследованы некоторые особенности получения покрытий на поверхности алюминия электроискровым легированием электродом из сплава Al-Sn, при котором в покрытии происходит образование нанонитей из SnO_2. Исследована износостойкость таких покрытий в условиях сухого трения в паре с закаленной сталью. Определены условия, при которых проявляется наибольший эффект превышения износа контртела относительно износа покрытия, содержащего нанонити SnO_2. В условиях сухого трения в наибольшей степени эффект проявляется после обработки в режиме «обыскривания» при постоянном количестве электричества пропускаемого через межэлектродный промежуток (при высоких скоростях перемещения электрода-инструмента относительно образца и относительно больших временах электроискрового воздействия на обрабатываемую поверхность).

Ключевые слова: электроискровое легирование, сплав Al-Sn, нанонити из SnO_2, износостойкость.