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Microgeometrical characteristics of electrospark coatings in the initial state

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Abstract

Microgeometric parameters of the effect of discrete electrospark coatings on their stress-strain state have been evaluated for the case of using a combined technology of modification of duralumin D16, which includes the technique of electrospark alloying with subsequent surface plastic deformation of coatings formed. According to the profilograms of discrete electrical coatings, the curves of the bearing surface (Abbott curves) were constructed and the parameters that drastically affect tribological characteristics of the coatings were determined. It was shown that modification of duralumin D16 with a combined electrospark coating VK-8 + Cu reduces the arithmetic mean height of peaks in the top portion of the profile by 4.4 and 3.2 times, doubles the arithmetic mean depth of the profile core irregularities, increases the arithmetic mean depth of profile valleys by 1.8 and 1.1 times, in comparison with electrospark coatings from hard alloy VK-8 and copper, respectively. These parameters help to reduce the period of running-in of the contact surfaces strengthened by the combined electrospark coating VK-8 + Cu, increase their bearing capacity, contact durability and specific oil consumption. On the basis of the finite element analysis method of the Nastran software complex, a model of the stress-strain state of a discrete coating/base was designed and distribution of the main normal stresses was determined for a coating compactness of 60% under a normal load of 600 N. The performed modeling revealed advantages of a combined technology for formation of wear-resistant electrospark coatings, which consists in turning residual tensile stresses into compressive ones. When modifying the duralumin D16 with a VK-8 + Cu coating, on the coating surface and in the base material, compressive stresses (-93 MPa and -20 MPa, respectively) are formed, which provides a decrease in wear of the modified surface by two times compared to unmodified duralumin D16.

The practical importance of the work consists in improving the wear resistance of aluminum alloy through its surface modification with functional coatings using energy saving technologies.

Key words: elektrospark alloying, discrete coating, Abbott curve, stress-strain state.

Introduction

The widespread use of aluminum and aluminum-based alloys in transport engineering is determined by high specific strength, increased corrosion resistance, as well as the ability to damp vibrations and high energy absorption. When choosing a structural material for tribocoupling, the main requirements are the ability to provide high antifriction and mechanical properties during operation. An efficient way to improve the mechanical characteristics of aluminum alloys is their surface hardening. A promising trend for modifying a surface layer is the use of the method of electrospark alloying (ESA), which has a unique set of advantages that meet modern requirements: low energy consumption, environmental safety, simplicity of technology (no special working medium and no preliminary surface preparation are needed) and high adhesion strength to the base. Electrospark processing provides the formation of a layer on the workpiece surface which has a structure and properties different from those in the initial state, depending on the parameters of the spark discharge, composition of the electrode material, workpiece material and other factors. The use of ESA to increase the microhardness of near-surface layers and the wear resistance of aluminum alloys is a topical trend in the current applied science.

Literature review

The solution to the problem of hardening the surface layer of aluminum alloys will provide an increase in wear resistance and fatigue strength, change in the magnitude and sign of residual stresses, etc. Despite the obvious advantages of the ESA method, it has some disadvantages, which include both an increase in the roughness of the modified layer and limitation for the applied coating depth. The main reasons for the latter are the occurrence of residual tensile stresses, including those due to the formation of new phases in the alloyed layer with different thermal expansion coefficients, which increases the likelihood of cracking in the applied coating [1].

Taking into account the disadvantages of continuous electrospark coatings (ESC), consisting in cohesive cracking and adhesive delamination, a technology of hardening and restoration by applying coatings of a discrete structure has been developed at H.S. Pisarenko Institute for Problems of Strength of NAS of Ukraine. The main advantage of discrete coatings is the ability to create conditions for regulating the temperature regime, achieving the lowest coefficient of friction and wear, to control and minimize the stress-strain state (SSS) of the surface via changing the continuity and dimensions of discrete areas on the base surface, as well as via selecting a set of materials with required physical and mechanical characteristics [2].

To reduce the initial roughness of electrospark coatings and to change the magnitude and sign of residual stresses, it is advisable to use ESA technology combined with surface plastic deformation (SPD), which makes it possible to form a surface layer with high hardness, wear resistance, low roughness and increased fatigue strength [3, 4].

It has been shown [5] that during ESA residual tensile stresses arise in the surface layer down to 0.2 mm deep. As a result of the subsequent hardening of the formed electrospark coatings thanks to SPD by rolling with a ball, the deformation curves change markedly: compressive stresses up to 520 MPa at a depth of to 0.9 mm are formed in the surface layer. Similar qualitative results were obtained in [6], where it was experimentally established that during plastic deformation of electrospark coatings, residual tensile stresses (43...59 MPa) turn into residual compressive stresses (–34… –80 MPa) down to a coating depth of 79–210 μm. This phenomenon occurred due to strain hardening caused by structural changes (in particular, by increase in the density of dislocations).

The performance characteristics of machine parts and mechanisms to a great extent depend on the parameters of the working surface quality, among which such microgeometrical characteristics as waviness, roughness, central height of microirregularities et al. should be mentioned first of all alongside with physical and mechanical properties (thickness, structure and phase composition of the hardened layer) [7]. The parameters of the surface layer quality directly determine tribological characteristics of triboelements. An increase in the coefficient of friction with increasing height of roughness parameters and its decrease along with wear, an increase in contact vitality with increasing the bearing curve of the profile have been established in the work [8].

The roughness of the surface layer directly affects the service life of friction pairs since microirregularities act as concentrators of stresses and may lead to a decrease in fatigue resistance. Practical operation of machines and mechanisms has shown that the wear intensity of the contact surfaces is dependent on the duration of running-in period, oil consumption, area of actual contact and other parameters determined by the curve of the bearing surface (Abbott curve) [9].

Thus, study of the features of modified layer formation on the surfaces of workpieces under a combined technology of ESA and PPD, the establishment of relationship between the substructure parameters, SSS of the modified layer and its tribological characteristics is an urgent task in terms of developing technological recommendations for strengthening parts in order to increase the overhaul life of units and assemblies.

Purpose

The purpose of the work was to evaluate microgeometric parameters of discrete electrospark coatings and their SSS using a combined technology for modifying duralumin D16.

Methods

Model annular samples of friction pair were made of steel 30KhGSA and duralumin D16, on the surface of which test alloys were deposited by the electrospark method using a standard industrial installation "Elitron 22A" in air at a specific duration of surface processing 1 min/cm2. The electric pulse duration was 200 μs.

As coating materials, hard alloy VK8 and copper, the physical-mechanical properties of which are listed in Table 1, were used.

Table 1

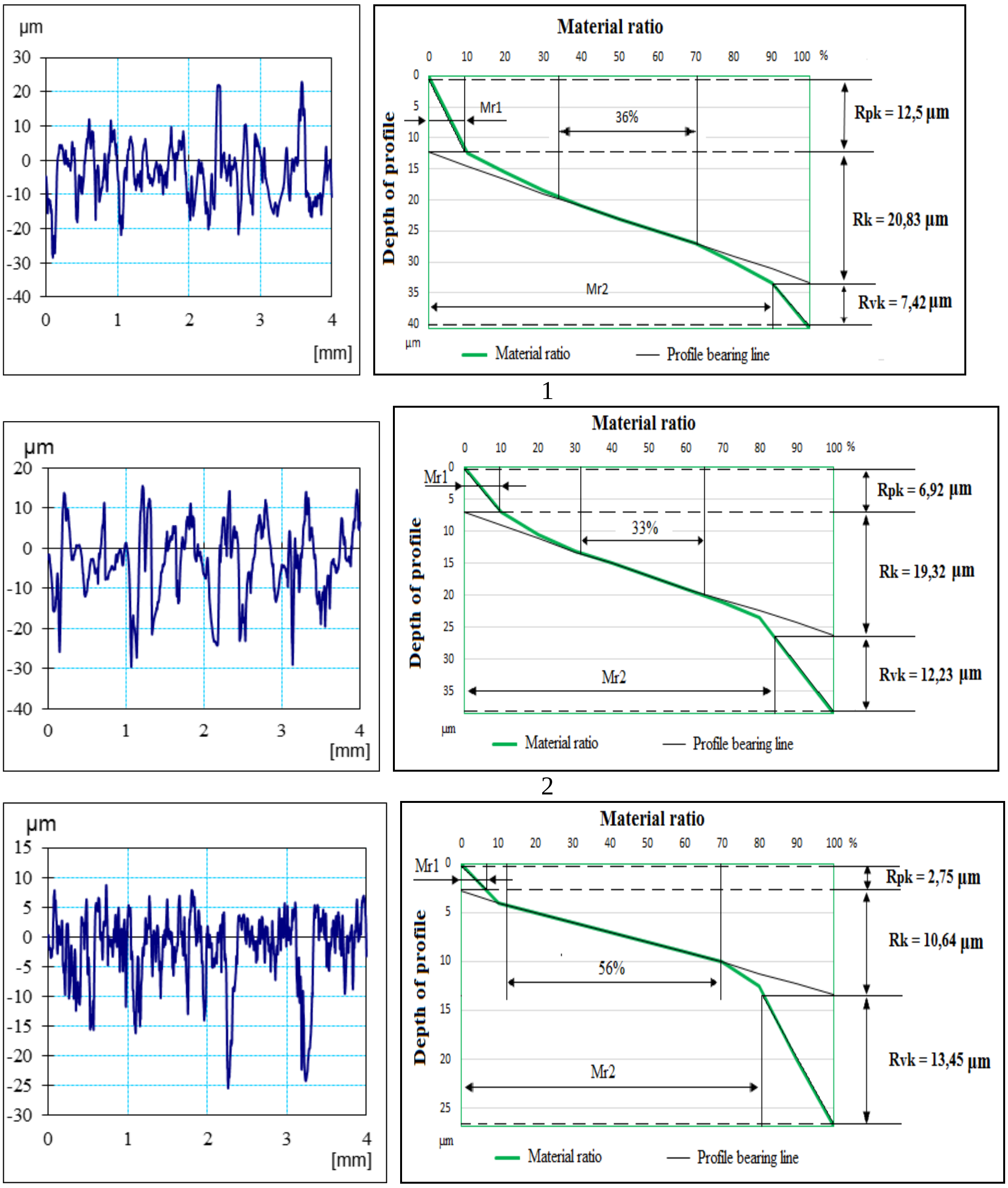
Physicomechanical properties of duralumin D16, alloy VK8, and Cu

Properties	D16	VK8	Cu
Density, kg/m^3	2800	14600	8940
Linear expansion coefficient, $\cdot 10^{-6}$, K^{-1}	23	45	16.7
Coefficient of thermal conductivity, Wt/(m·K)	170	54	401
Specific heat, J/(kg·K)	1000	150	385
Young's Module, $\cdot 10^{11}$ Pa	0.71	6.0	1.15
Shear Module, $\cdot 10^{11}$ Pa	0.27	2.5	4.24
Poisson's ratio	0.3	0.196	0.33

Parameters of surface microrelief profile were determined according to the international standard DIN 4776 [10].

Results

On the basis of ESC profilograms, Abbott curves were constructed and the main parameters of the surface profile were analyzed (Fig. 1, Table 2).



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2

3

Fig. 1. Profilograms of the ESC surfaces and functional parameters for the roughness profile from the Abbott curve: (1) VK-8; (2) Cu; (3) VK-8 + Cu.

Table 2.

Functional parameters of the profile of surface microrelief roughness

Parameters of profile of surface roughness	Type of electrospark coating		
	VK-8	Cu	VK-8 + Cu
R_{pk}, arithmetic mean height of the profile top peaks, μm	12.15	6.92	2.75
R_k, arithmetic mean core depth of profile microirregularities, μm	20.83	19.32	10.64
R_{vk}, arithmetic mean depth of profile valleys, μm	7.42	12.23	13.45
R_a, arithmetic mean deviation of profile, μm	6.29	6.53	4.2
Mr1, material ratio that determines the upper limit of core roughness, %	8	10	7
Mr2, material ratio that determines the lower limit of core roughness, %	89	83	81
Central part of mean relative bearing profile length, %	36	33	56
Q, specific surface oil consumption, mm^3/cm^3	0.041	0.104	0.128

An important stage in the initial operation of machine parts is the duration of running-in period. It is in this stage that the primary condition for contacting triboelements is growth of the actual contact area. It is possible to reduce the running-in period by minimizing the profilogram portion that corresponds to the peaks in the upper part of the profile. According to Table 2, for the combined coating VK-8 + Cu parameter R_{pk} is 2.75 μm, which indicates the most effective ability of this coating type to shorten the running-in period.

The parameter R_k allows one to predict the operational properties of the surface and directly affects the service life of triboelements, since this zone in the core of the profile microirregularities determines the bearing capacity and load distribution in the contact. As the combined coating VK-8 + Cu is characterized by a decrease in this parameter on average twice compared to the other ESC studied, it is possible to predict its high efficiency after the formation of microrelief upon using the combined technology of ESA and PPD. The level of coincidence of the region of maximum increase in material ratio of the surface microrelief profile on the Abbott curve and the reference line of the surface roughness profile for VK-8, Cu, VK-8+Cu coatings is 36; 33; 56 %, respectively (Fig. 1). According to the method of evaluation of this parameter by the DIN 4776 standard, its recommended values are around 40%. Only for the VK-8 + Cu coating, increase in this parameter by 1.4 times in comparison with the normalized value was established. The obtained results indicate that the combined coating VK-8 + Cu in the initial state is characterized by the maximum material increase in the core zone of the surface profile, which is decisive in predicting the service life of the contact surface.

An important Abbott curve parameter is the arithmetic mean depth of the profile valleys, which determines the oil consumption by the tribological surface. The specific oil consumption of the surface was calculated by the formula [9]:

$$Q = \frac{R_{vk}}{20}\left(1 - \frac{M_{r2}}{100\%}\right), \tag{1}$$

where R_{vk} is the arithmetic mean depth of the profile valleys and M_{r2} is the material ratio that corresponds to the lower limit of core roughness, %.

According to Table 2, the calculated data on specific oil consumption for the combined ESC VK-8+Cu are 3.12 and 1.23 times higher than the similar parameters for VK-8 and Cu coatings, respectively. The parameter Q directly affects antifriction characteristics of the coatings studied: for VK-8, Cu, VK-8 + Cu the coefficient of friction in the contact is 0.17; 0.13; 0.11, respectively. Therefore, the VK-8 + Cu coating in terms of the surface microrelief profile R_{vk} will be characterized by high lubrication and antifriction properties, which is a necessary condition for increasing the durability of tribocoupling under operation conditions in a lubricating medium.

The paper indicates reasonability of using the combined technology for duralumin D16 modification, which includes ESA with subsequent treatment of the formed coatings by SPD. The method of finite element analysis, which is implemented in the Nastran software package, was used to model the electrospark coating density and evaluate its SSS. The studied ESCs were applied onto duralumin D16 with a compactness of 60%. When modeling the SSS of discrete coatings, the residual tensile stresses on the surface of a unit coating were revealed, which were 99, 17 and 57 MPa for coatings VK-8, Cu and VK-8 + Cu, respectively. Since such stresses can reduce wear resistance of the contact surfaces, SPD was performed after ESA by technique of static embossing with a maximum load of 190 MPa ($\sigma_T^{0,7}$ for D16). The combined technology was used in order to increase the tribological ESC properties through turning the residual tensile stresses in the formed ESCs into residual compressive stresses after SPD (Table 3, Fig. 2).

Table 3

Distribution of the main normal stresses in the electrospark coating/base after electrospark alloying (ESA) and subsequent processing of the formed coatings by surface plastic deformation (SPD)

Coating material	Distribution of main normal stresses, σ_z, MPa					
	On ESC surface		At ESC/base (D16) boundary		In the base (D16) at 150 μm depth	
	ESA	ESA+SPD	ESA	ESA+SPD	ESA	ESA+SPD
VK-8	99	-20	47	37	2	-2
Cu	17	-97	5	-4	-2	-7
VK-8 + Cu	57	-93	27	17	2	-20

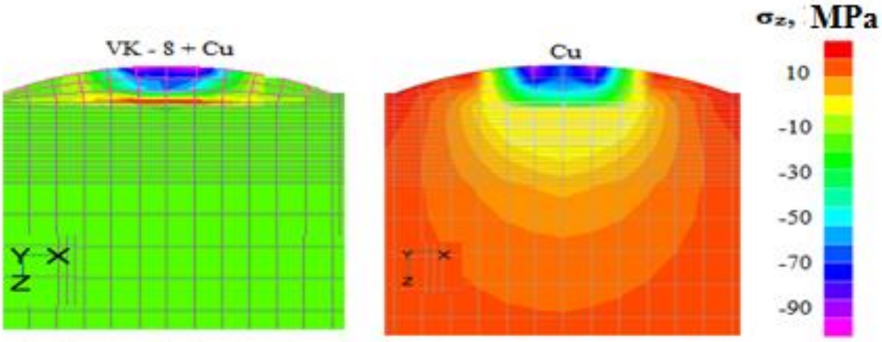

Fig. 2. Distribution of the main normal stresses in ESC/base upon using a combined technology for modification of duralumin D16.

The performed simulation of SSS of a discrete ESC/base has revealed the following advantages of using the combined technology for forming wear-resistant ESCs: on the coating peaks the magnitude and sign of residual stresses change, that is, after ESC tensile stresses turn into compressive ones; when hard alloy VK-8 + copper are used as a coating, the localization of the main normal stresses is observed in the coating formed, in contrast to the coating from copper alone; in the base material from duralumin D16 modified with a coating VK-8 + Cu, compression stresses are formed. These factors increase the wear resistance of contact surfaces: when rubbing in sliding conditions (tests were conducted on a friction machine 2070 SMT-1 for 240 min in the mode of maximum lubrication with an oil consumption of 1.2 l/h; one sample D16 + coating rotated with a frequency of 400 min-1, and the other one (stationary, steel 30HGSA) was installed coaxially, their end faces were pressed together with an axial load of 600 N; as a lubricating medium, motor oil M10G2K (GOST-8581-78) was used), it was established that wear of the contact surface D16 + VK-8 increased by 4.6 times, while modification of the base with Cu coating or combined coating VK-8 + Cu provided wear reduction by 5 and 2 times, respectively, compared to unmodified (with a coating) base D16.

Conclusions

According to the microgeometric parameters of the microrelief profile of discrete electrospark coatings, Abbott curves have been constructed and the parameters that influence coating wear resistance most of all have been determined. In particular, reduction of the arithmetic mean height of the peaks in the upper part of the profile shortens the running-in period for the contact surfaces; growth of the arithmetic mean depth of the core of the profile micro-irregularities provides an increase in load-bearing capacity and determines the load distribution in the contact; increase in the arithmetic mean depth of the profile valleys is the main prerequisite for increasing the specific oil consumption of the surface and ensuring high lubrication and antifriction properties of the tribocontact. The application of the developed combined technology to forming discrete wear-resistant coatings on duralumin D16 is proposed, which includes electrospark alloying followed by surface plastic deformation, which provides the formation of residual compressive stresses and localization of the main normal stresses in the coating formed.

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Токарук В.В., Мікосянчик О.О., Мнацаканов Р.Г., Рогожина Н.О. Мікрогеометричні характеристики електроіскрових покриттів в вихідному стані

Проведена оцінка мікрогеометричних параметрів дискретних електроіскрових покриттів на їх напружено-деформованого стану при використанні комбінованої технології модифікування дюралюмінію Д16, яка включає метод електроіскрового легування з наступною поверхнево пластичною деформацією сформованих покриттів. За профілограмами дискретних електроіскрових покриттів побудовані криві опорної поверхні (криві Аббота) та визначені параметри, які найбільше впливають на триботехнічні характеристики покриттів. Визначено, що модифікування дюралюмінію Д16 комбінованим електроіскровим покриттям ВК-8+Cu забезпечує зменшення середньої арифметичної висоти виступів верхньої частини профілю в 4,4 і 3,2 рази, зростання середньої арифметичної глибини серцевини мікронерівностей профілю в 2 рази, збільшення середньої арифметичної глибини впадин профілю в 1,8 і 1,1 рази, в порівнянні з електроіскровими покриттями твердого сплаву ВК-8 та міді відповідно. Дані параметри сприяють скороченню періоду припрацювання контактних поверхонь, зміцнених комбінованим електроіскровим покриттям ВК-8+Cu, підвищують їх несучу здатність, контактну довговічність, питому маслоємність поверхні.

На основі методу скінченно-елементного аналізу програмного комплексу Nastran проведено моделювання напружено-деформованого стану дискретного покриття - основи та визначено розподіл головних нормальних напружень при щільності нанесення покриття 60% та нормальному навантаженні 600 Н. Проведене моделювання встановило переваги застосування комбінованої технології формування зносостійких електроіскрових покриттів, які полягають в зміні залишкових напружень розтягу на напруження стиску. При модифікуванні дюралюмінію Д16 покриттям ВК-8 + Cu на поверхні покриття та в матеріалі основи формуються напруження стиску (-93 МПа та -20 МПа відповідно), що забезпечує зниження зносу модифікованої поверхні в 2 рази, в порівнянні немодифікованим дюралюмінієм Д16.

Практична значимість роботи полягає в підвищенні зносостійкості алюмінієвого сплаву шляхом його поверхневого зміцнення функціональними покриттями з застосуванням енергозберігаючих технологій.

Ключові слова: електроіскрове легування, дискретні покриття, крива Аббота, напружено-деформований стан.