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Research into morphology and phase structure in the surface of Al-Si alloy modified by yttrium oxide

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Abstract. Using methods of physical material studies (scanning electron microscopy and micro X-ray spectral analysis), a study was carried out with focus on alteration of structure and phase composition in surface layers of Al-Si alloy (silumin AK10M2N) treated in electroexplosive alloying with a multiphase plasma jet formed in the process of aluminum foil explosion and carrying particles of Y_2O_3 weighted powder portion. It was revealed that a porous surface layer with non-homogeneously distributed alloying elements (silicon, yttrium) in it is formed in any conditions of electroexplosive alloying of silumin. Thickness of the modified layer is different, varying 50 to 160 μm, depending on the zone to be examined. The modified surface consists basically of Al, Si and Y. Yttrium in the modified layer is thought to be an indirect evidence of better physical and mechanical properties of the surface layer in comparison with the base material.

Key words: silumin, microstructure, electroexplosive alloying, yttrium oxide.

1. Introduction

To date, engineering and technology are challenged with the need to develop and manufacture new materials with satisfactory operational properties. Since the surface of machine parts tends to get fractured while in operation, efforts are made to elaborate methods for strengthening and protection of the surface involving modification of properties in material surface or coating. This is a technique of surface treatment by concentrated energy flows, e.g. laser emission [1–3], electron beams [4, 5] and plasma [6, 7]. It is characterized by pulse and local effect on the surface; that is supposed to be a significant economic advantage over stationary techniques. Furthermore, a number of treatment parameters and their combinations can be set, so new structure and phase states are possible in formed surface layers of materials with advanced properties.

This study focuses on formation of coatings by means of electroexplosive alloying. This technology enhances strength, durometric and tribological properties of the modified material. Strengthening is possible due to formation of coatings with fine-dispersed phases in a viscous metallic matrix. As a consequence of electroexplosive alloying, physical and mechanical properties, such as micro-hardness, impact resistance, durability, as well as frictional characteristics can be changed significantly.

Industrial Al-Si alloy – silumin AK10M2N was used as a material for research. It was a well-weighted decision because aluminum and aluminum-based alloys show a number of unique properties and are widely applied in mechanical engineering, aircraft and car building. To modify the surface yttrium oxide powder (Y_2O_3) was used in the study. This powder is broadly applied in the present day material studies for the development of advanced oxidation-resistant materials and manufacturing of highly efficient alloys [8, 9].

Up to now, far little attention has been paid to interrelation of chemical composition, structure and mechanical properties. Improvement of mechanical properties via various modification techniques hasn't found sufficient reasoning yet. Different research groups all over the world have been working on this issue. These studies are focused on the influence of thermal treatment of aluminum and aluminum-based alloys, deformations in different conditions, alloying, and plasma treatment on modification of properties in the initial material [10–17].

2. Material and experiment methods

Al-Si alloy AK10M2N was used as a material for research. Using the method of X-ray spectral analysis, chemical composition of analyzed samples was defined with the help of an energy-dispersion detector of micro X-ray spectral analysis INCAx-act; as revealed, main elements in the composition are Al – 84.88% and Si – 11.10%. Principal alloying elements are Cu – 2.19%, Ni – 0.92%, and Mg – 0.58%.

Samples to be analyzed were $20\times20\times10$ mm^3 and oriented perpendicular to the axis of a plasma jet. Electroexplosive alloying was carried out using a laboratory pulse discharge unit EVU 60/10M [18]. Capacity storage of unit EVU 60/10M is discharged with a current density of approximately 10^{10} A/m^2 on the conductor to be exploded, which was fixed on the electrodes of a coaxial end-type plasma accelerator. Multiphase plasma, generating in electroexplosive destruction of a conductor, gets a shape of a jet, which influences on the surface.

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As for construction, electroexplosive unit EVU 60/10M consists of three main parts (Fig. 1): charger – 2, comprising an autotransformer, a step-up transformer and a rectifier; capacity storage – 3; plasma accelerator – 4. The unit is operated manually – it is charged and discharged via pressing particular buttons on the remote control – 1. A process chamber, where electroexplosive alloying is conducted, is connected with a prevacuum pump (5), controlled with the remote (1).

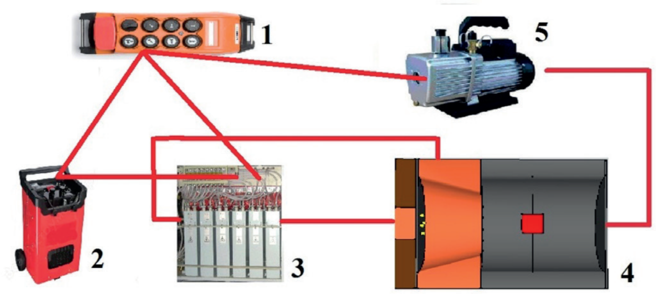

Fig. 1. Structural layout of electroexplosive unit EVU 60/10M. 1 – remote control, 2 – charger, 3 – capacity storage, 4 – plasma accelerator and process chamber, 5 – prevacuum pump

When a capacity storage discharges, high density electrical current flows through electrodes (2) and conductor (6) (Al foil) to be exploded, causing, this way, its explosion (Fig. 2). The products of explosion are drawn into the vacuum process chamber (3) (residual pressure 100 Pa), carrying particles of the weighted powder portion (Y_2O_3 is used for the purpose of research). The sample is placed in the vacuum process chamber at various distances from the nozzle and fixed with holders of samples (4). The products of electric explosion are a multiphase system, comprising both plasma component (Al) and condensed particles with different dispersion (Y_2O_3), which set on the surface of the treated product and form a multicomponent coating (8). A supersonic front edge of the jet flowing over the surface and reflecting from it causes formation of a shock-compressed layer with high temperature and pressure. The surface is heated up to the temperature of melting and above it over a short time of pulse plasma impact.

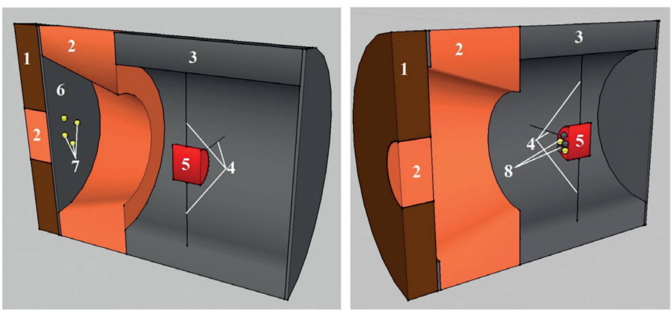

Fig. 2. A layout of a pulse plasma accelerator. 1 – insulator, 2 – outward ring and inner cylindrical electrodes, 3 – vacuum process chamber, 4 – holders of samples, 5 – a sample to be treated, 6 – exploded conductor (Al foil), 7 – a weighted Y_2O_3 powder portion, 8 – plasma consisting of atoms Al and Y_2O_3

Aluminum foils were used as a material of exploded conductors, and Y_2O_3 – as a weighted powder portion. Surface treatment of silumin was carried out in six treatment conditions, differing in the voltage of discharge and weights of a weighted powder portion. The conditions are given in Table 1.

Table 1
Conditions of electroexplosive alloying

№ treatment conditions	**Aluminum foil weight (g)**	**Y_2O_3 powder weight (g)**	**Voltage of discharge (kV)**
1	0.0589	0.0589	2.6
2	0.0589	0.0589	2.8
3	0.0589	0.0295	2.6
4	0.0589	0.0295	2.8
5	0.0589	0.0883	2.6
6	0.0589	0.0883	2.8

The coating generated in the process of electroexplosive alloying was analyzed with the help of a scanning electron microscope TESCAN Vega SB equipped with a tungsten cathode with thermo-electron emission, four-lens electron optics Wide Field Optics, and using an “intermediate lens” for adjusting form and size of a beam. Resolution in conditions of high vacuum was set 3.0 nm at a voltage of 30 kV.

Samples were photographed in the mode of back-scattering and secondary electrons. Micro X-ray spectral analysis was carried out with the help of an add-on device to the electronic microscope TESCAN Vega SB of energy-dispersion X-ray detector and multichannel spectrum analyzer INCAx-act. For the purpose of micro X-ray spectral analysis separate zones were examined, as well as distribution patterns of elements on the surface or along the set line were recorded. The accelerating voltage was set according to dimensions of the object under consideration.

Both the surface and micro-sections perpendicular to the treated surface and deep into the material were analyzed. Images given in this paper are made on the secondary electrodes and in conditions maximally similar to optic imaging.

3. Results and discussion

3.1. The structure of alloy analyzed in the initial state. Figure 3 shows a typical structure of an etched micro-section in the initial state, SEM-imaging.

A multi-phase, morphologically heterogeneous structure of the material is demonstrated in the microphotograph above. The micro-structure of alloy comprises grains of solid solution and Al-Si eutectic with diverse morphology. Using methods of

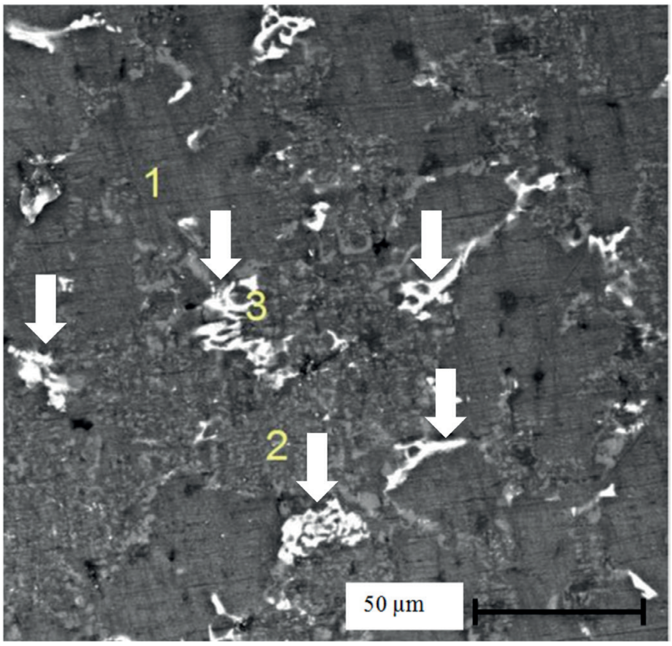

Fig. 3. Micro-structure of silumin, SEM-imaged on the etched micro-section; areas are shown where micro X-ray spectral analysis of material element composition was conducted

selective etching on edges of α-solid solution grains, intermetallics AlNiCu and AlMg are found.

The findings of local micro X-ray spectral analysis of a particular inclusion are given in Table 2.

Table 2
Element composition in particular areas of the initial structure, its electron-microscopic image is given in Fig. 2.
The results are in wt.%

Area	Mg	Al	Si	Fe	Ni	Cu
1	0.17	96.46	1.67	0.02	0.04	1.64
2	0.30	74.98	22.80	0.04	0.12	1.76
3	0.44	64.16	0.83	0.71	24.36	9.50

As seen in Table 2, alloying elements are distributed quite non-homogeneously in the material, forming compounds, varying in size, level of contrast, morphology and element composition.

3.2. Analysis of the structure in the modified surface. Figure 4a gives a general view of a sample subjected to electroexplosive alloying. As seen, the coating is porous and has craters. It is revealed that pores can vary 10 to 50 µm irrespectively of treatment conditions (Fig. 4).

In some areas there are parts of aluminum foil, which were not crumbled up in electric explosion, and particles of yttrium oxide carried towards the surface of the treated material when moving, and setting afterwards on the surface in form of blocks 100 to 200 µm (Fig. 5). This fact is confirmed by

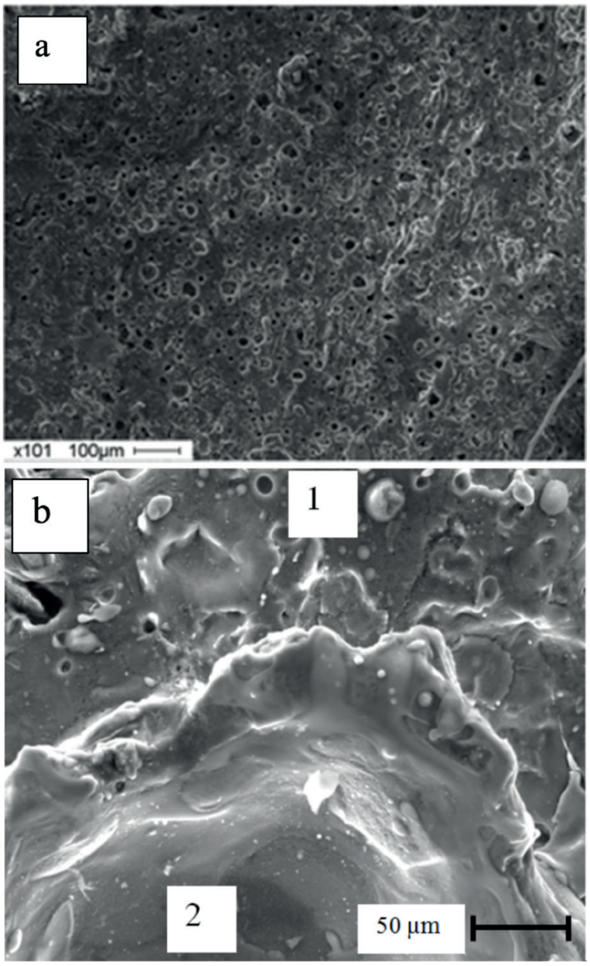

Fig. 4. The structure of silumin surface, treated by electroexplosive alloying; b indicates areas, where micro X-ray spectral analysis of element composition in the material was carried out. SEM

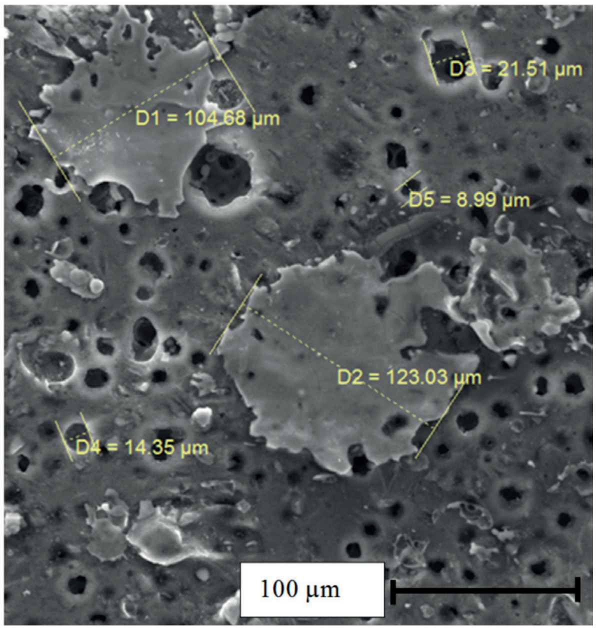

Fig. 5. Dimensions of Al foil parts not crumbled up in electroexplosive alloying

the data of micro X-ray spectral analysis (Table 3) in areas shown in Fig. 4b.

Table 3
Element composition in several areas of the treated surface, its electro-microscopic image is given in Fig. 3b. The data are in wt.%

Area	O	F	Mg	Al	Si	Ti	Fe	Ni	Cu	Y
1	18.49	1.84	0.48	43.26	4.04	13.26	0.42	5.25	1.63	9.87
2	19.35	1.90	0.18	10.85	1.08	6.89	0.51	7.03	4.20	45.31

According to the data, chemical composition in Area 1 shown in Fig. 3b comprises mainly Al – 43.26%, Ti – 13.26% and Y – 9.87%. Area 2 contains a lot of yttrium (45.31%), confirming the assumption of originating blocks on the treated surface.

In some areas of the coating there are zones with an apparently non-homogenous structure and a lot of cracks, formed as a result of high-speed cooling (Fig. 6). This special feature is detected only in treatment conditions 5 and 6.

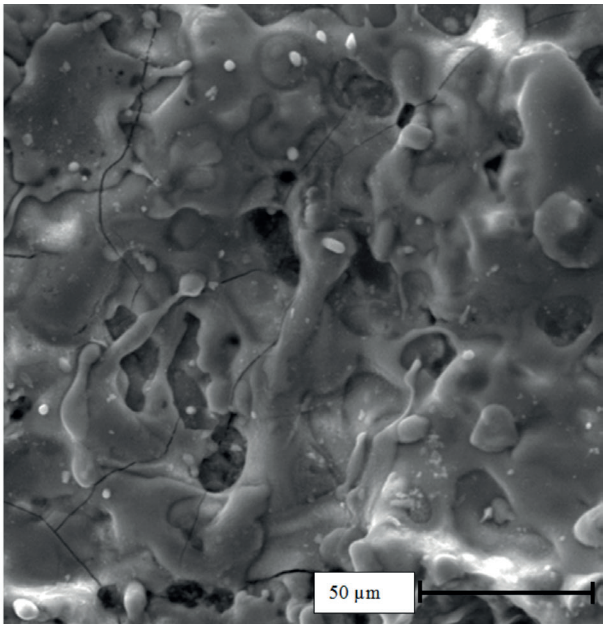

Fig. 6. Micro-cracks on the treated surface after electroexplosive treatment

3.3. Analysis of micro-structure in the crosscut section of alloy, modified by electric explosion. Using methods of micro X-ray spectral analysis, microstructure and element composition of silumin treated in electroexplosive alloying were studied in different zones of a sample.

It is seen in micro-photographs (Fig. 7) that thickness of the modified layer is different, irrespectively of treatment conditions, varying 50 to 160 µm according to the zone of analysis. The study on the structure in the crosscut section of the electro-explosively modified sample indicates that the treated

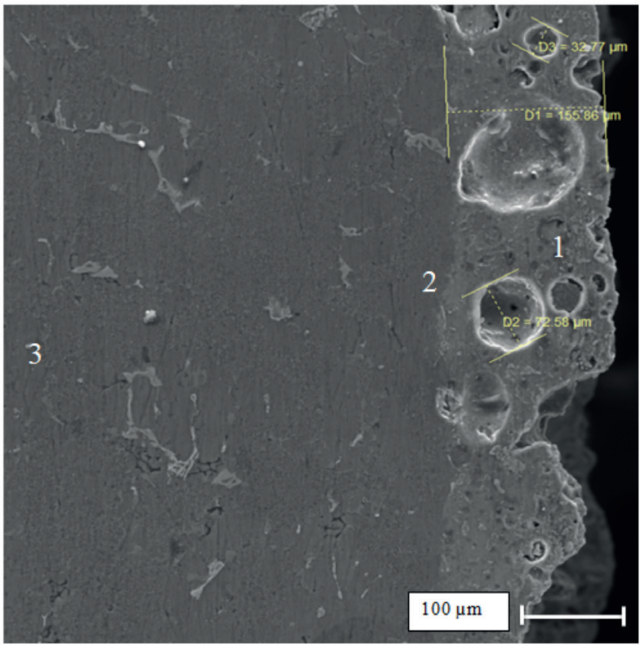

Fig. 7. Micro-structure of the crosscut micro-section in the sample modified by electric explosion

surface is porous with a high number of craters and pores with diameter varying 5 to 80 µm.

Element analysis of different zones in the crosscut micro-section (Fig. 7) carried out at different depths from the treated surface is given in Table 4.

Table 4
Element composition in zones of the crosscut micro-section in the sample, its electron-microscopic image is shown in Fig. 6. The data are in wt.%

Zone	Mg	Al	Si	Ti	Cu	Y
1	0.91	80.34	11.78	0.81	2.04	2.50
2	0.22	90.91	4.55	0.04	2.78	0.14
3	0.21	93.44	4.97	0.04	0.94	0.39

Based on the data of the element composition in zones of the crosscut section in the sample, a conclusion is made that the modified layer consists (Zone 1) mainly of Al, Si and alloying elements, and Y (2.5%), which is in the structure of the modified layer due to electroexplosive alloying. Yttrium in the modified layer can improve mechanical properties of the surface. Chemical composition of Zone 2, which is close to the modified surface, is similar to the material except for the increased concentration of Cu.

4. Conclusion

The study revealed that alloy microstructure in the initial state consists of solid solution grains and Al-Si eutectic of diverse morphology. Using methods of selective etching on borders of α-solid solution grains, intermetallics AlNiCu and AlMg were found. Alloying elements are spread quite non-homogeneously in the material, forming compounds with different dimensions, morphology, level of contrast and element composition. In the process of surface modification a highly-porous coating with lots of craters is generated. According to the results of the study pores vary 10 to 50 μm irrespectively of treatment conditions. Zones with highly heterogeneous structure, and lots of cracks formed in the process of high-speed cooling were detected in some zones of the coating. Thickness of the modified layer is different varying 50 to 160 μm in various zones to be analyzed. The modified layer consists mainly of AL, Si and Y. Physical and mechanical characteristics of the modified layer are supposed to be improved because of yttrium in the surface layer.

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