Study of the surface relief, structure and phase composition of the silumin composite layer obtained by the method of electric explosion alloying by Al-Y$_2$O$_3$ system

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Abstract. The studies of the surface relief, structure and phase composition of silumin surface layer modified by the electric explosion of the aluminium conductor with the weighed sample of yttrium oxide were done by the methods of modern physical material science (atomic-force and transmission electron microscopy) in the research. It is stated that the multi-layer structure which consist of the highly porous coating inhomogeneous in thickness, the liquid phase alloying layer and the thermal effect layer, is formed in the top layer. It is revealed that the top layer possesses a submicro- and nanodimentional multi-phase structure. The particles of silicon, Y$_2$O$_3$, YSi$_2$ and Y$_2$Si$_2$O$_7$ are the hardening phases of this structure. It consists of the cellular crystallization structure being characterized by the inhomogeneity in the distribution of the alloying elements.

1. Introduction
As for the positive characteristics of silumin as a material it should be noted that in the properties of hardness and corrosion it is close to stainless steel, however its weight is several times less than that of steel. The hardness properties of the alloy are ensured by the silicon being a part of it and the corrosion resistance is ensured by the formation of the protective oxide film appearing on the surface in the oxidizing media, one of which is oxygen. The advantage of silumin is its plasticity, the alloy easily repeats the most complex forms, filling them uniformly. As a result the casting of silumin is simplified and it means that the production process becomes cheaper [1].

Owing to these properties silumins found a wide application as structural materials in machine-building, aircraft construction, automobile manufacture. However, the hardness properties of silumins become less enough from year to year in the conditions of the intensively developing technologies and it leads the researchers to the need for the modification of the materials.

The promising methods permitting to harden and protect the surface by the modification of its properties are the concentrated flows of energy such as the electron beam [2, 3], laser radiation [4, 5] and plasma effects [6, 7]. The main feature of the given methods is the fact that they have the pulse and local character of effect to the surface, and it has the significant economic advantage in their application.
compared with the traditional methods of treatment such as alloying [8, 9], thermal treatment [10, 11], pressure shaping.

In the case of the electric explosion alloying the hardening is reached at the expense of the coating formation with the creation of the fine dispersed phases in the tough metallic matrix resulting in the multiple change in the physical and mechanical properties: microhardness, shock resistance, durability, friction properties [12].

In this connection the purpose of the research is the study of the surface relief, structure and phase composition of the silumin composite surface layer obtained by the method of electric explosion alloying by Al-Y_2O_3 system.

2. Experimental method and material
The electric explosion alloying was done using the laboratory charge-pulsed electric explosion unit EVU 60/10 [13]. It includes the capacitive energy storage and the pulsed plasma accelerator consisting of coaxial face system of electrodes (2) with the conductor (6) fixed on them, the discharge chamber localizing the products of explosion and directing them to the nozzle along which they blow into the vacuum technological chamber (3) with the residual pressure of 100 Pa. The electric explosion takes place as a result of the transmission of high density electric current (of the order of 10^10 A/m^2) through the conductor with the discharge of the storage (figure 1).

![before_after.jpg](image)

**Figure 1.** The diagram of the pulsed plasma accelerator 1 – insulator, 2 – external circular and internal cylindrical electrodes, 3 – vacuum technological chamber, 4 – sample holders, 5 – sample being treated, 6 – conductor (Al foil) being exploded, 7 – powder weighed sample Y_2O_3, 8 – plasma consisting of Al and Y_2O_3 atoms.

The multi-phase plasma (in our case, plasma consists of the particles of aluminium foil serving as the exploded conductor and yttrium oxide being a powder weighed sample), being formed in electric explosion destruction of the conductor, is formed into the jet being the means of the effect to the surface (8).The test material was the alloy of aluminium with silicon AlSi_{10}CuMg_{2}Ni. The chemical composition of the sample under test with the main elements of Al – 84.88% and Si – 11.10% was determined by the method of X-ray spectrum analysis with the energy dispersion detector of micro X-ray spectrum analysis INCAx – act. The dispersion of the alloying elements and impurities is shown in figure 2a. The main alloying elements are Cu – 2.19%, Ni – 0.092%, Mg – 0.58%.

The test samples had the dimensions of 20x20x20 mm^3 and they were oriented perpendicular to the axis of the plasma jet (figure 2b).

The surface treatment of silumin samples was done according to two optimal regimes differing in the discharge voltage and the masses of the powder weighed samples. The characteristics of the used regimes are given in table 1.

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**Table 1.**

| Regime  | Discharge Voltage (kV) | Mass of Powder Weighted Sample (g) |
|---------|------------------------|------------------------------------|
| Regime A | 15                     | 2                                   |
| Regime B | 20                     | 3                                   |

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Figure 2. Distribution of the alloying elements and impurities in silumin AlSi10CuMg2Ni (a), geometrical dimensions of the samples and the surface of treatment (b).

Table 1. Regimes of electric explosion alloying.

| № regimes | Mass of aluminium foil | Mass of powder Y2O3 (g) | Discharge voltage |
|-----------|------------------------|-------------------------|------------------|
| 1         | 0.0589                 | 0.0589                  | 2.8              |
| 2         | 0.0589                 | 0.0883                  | 2.6              |

The studies of the surface relief being obtained in electric explosion alloying and its local properties were performed using atomic force microscope NT-MDT Solver NEXT the probe (cantilever) of which was made by the method of liquid phase etching.

The defect substructure, elemental and phase composition of the top silumin layer subjected to electric explosion alloying were analyzed by the methods of the transmission electron diffraction microscopy of thin foils (device JEM – 2100F, JEOL). The foils for studying of structural phase composition of the material by TEM methods were made by ion thinning of plates h ≈100 µm thick cut from the sample by electric spark method (figure 1b). The plates cut in such a manner, were thinned by ion etching method (device Ion Slicer EM – 09100IS).

The photographs shown in the paper were taken in the secondary electrons in the regime nearest to the optical image.

3. Result and Discussion
The study of the surface morphology being formed after electric explosion alloying.

The topography of the sample’s surface profile obtained using atomic force microscopy is presented in figure 3. It shows 3D and 2D images as well as the cuts of the irregularity distribution along the base line in the main volume of the samples and on the coating.

The analysis of figure 3 shows that the top layer in the samples after electric explosion alloying is a high porous one independent of the regime of treatment. In the statistical analysis of the image the maximum of the pores’ depth was detected with the values of the order of 1500 nm for the regime 1 and 500 nm for the regime 2. It should be noted that the surface of the samples treated according to the regime 2 is characterized by the less quantity and pores’ depth than in the case of the treatment according to the regime 1. It may be explained by the fact that the particles of the plasma jet distributed more uniformly having less energy by reason of the larger mass of the weighed sample of the sprayed powder and the less energy effect.
Figure 3. Atomic force microscopy of surface profile of the sprayed sample’s layer: a – the distribution of the relief irregularities throughout the height in 3D format, b – 2D image of the topography of the surface profile with the base line, c – the distribution of the relief irregularities along the base length.
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Defect substructure, elemental and phase composition of silumin top layer after electric explosion alloying.

By TEM methods of thin foils it is determined that the electric explosion alloying is accompanied by the high speed cooling of the modified layer with the result that the structure of the cellular crystallization of aluminium (figure 4) is formed in the top layer. The size of the crystallization cells varies within 200-450 nm. The interlayers of the second phase locate along the boundaries of the cells. By the methods of micro – X – spectrum analysis it is determined that the interlayers are formed by the atoms of silicon and yttrium (figure 4bc).

Figure 4. Micro X-ray spectrum analysis (mapping method) of the elemental composition of silumin subjected to electric explosion alloying ( STEM method); a – light field image; b – image obtained in X-ray radiation of silicon atoms; c – image obtained in X – ray radiation of yttrium atoms.

It should be noted that the concentration of oxygen atoms is low that may be indirectly indicative of the absence of the oxide phase at the boundaries of the crystallization cells.

Figure 5a shows the electron microscope images of the silumin structure of the cellular crystallization. It is clearly seen that the cells are of the oval shape. The cell dimentions vary within 150-300 nm. The microdiffraction analysis showed that the cells were the solid solution based on aluminium (figure 5b). The particles of the second phase are revealed in the volume of the cells by the dark field analysis method; the dimensions of the cells vary within the units of nanometers (figure 5b).

The analysis of micrographs (figure 5b) suggests that these particles are the yttrium cildicides YSi2. The aluminium cells are divided by the interlayers of the second phase. The analysis of the micrograph (figure 5c) shows that the interlayers are formed by silicon and yttrium silicate Y2Si2O7.

4. Conclusion
The study of the surface morphology being formed after electron explosion alloying in silumun modified by Al–Y2O3 system by the methods of atomic force microscopy has shown that electric explosion alloying results in the formation of the multi – layer structure consisting of the high porous coating irregular in thickness, the layer of liquid phase alloying and the layer of thermal effect.
By the methods of the transmission electron diffraction microscopy it has been revealed that the electric explosion alloying of silumin is accompanied by the formation of the surface layer possessing the structure of cellular crystallization and being characterized by the irregularity in the distribution of the alloying elements (silicon, yttrium and oxygen), submicro- and nanodimentional multi – phase structure whose hardening phase is the particles of silicon, $Y_2O_3$, $YSi_2$ and $Y_2Si_2O_7$.

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References
[1] Belov N A, Savchenko S V and Khvan A Phase composition and structure of silumins 2008 (Moscow ; MISIS) p 282
[2] Deqiang W, Xiaobing W, Rong W and Hongyang C 2018. Vacuum 149 118
[3] Xuewei T, Zhengjun Y , Shasha Z, Jun L and Jing L 2018. Surface and Coatings Technology 337 418
[4] Oliveira V, Sharma S P, de Moura M F S F, Moreira R D F and Vilar R 2017. Optics and Lasers in Engineering 94 37
[5] Ahuir-Torres J I, Arenas M A, Perrie W and de Damborenea J 2018 Optics and Lasers in Engineering 103 100
[6] Min-Seok Jang, Sung W M, Jongsoo S, Myungmo S and Young-HoKim 2017. Microelectronics Reliability 78 220
[7] Farag O F 2018. Results in Physics 9 91
[8] Valkov S Petrov P, Lazarova R, Bezdushnyi R and Dechev D 2018. Applied Surface Science 389 768
[9] Han X, Conglin Z, Peng L, Jie C, Yunxue J and Qingfeng G 2018. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 41 69
[10] Czekaj E, Zych J, Kwak Z and Garbacz-Klepka A 2016. ARCH I VES of FOUNDRY ENGINEERING 16 25
[11] Gawdzińska K, Bryll K and Nagolska D 2016. Arch. Metall. Mater. 61 177
[12] Osintsev K A, Zagulyaeva D V., Konovalov S V and Shlyaroy V V 2017. AIP Conference Proceedings. 020159/1
[13] Romanov D A, Budovskikh E A, Zhmakin Y D and Gromov V E 2011 Steel in translation 41 464
[14] Shlyaroy V V, Osintsev K A, Butakova K A, Zagulyaev D V and Romanov D A 2017 Promising materials and technologies: International Simposium Proceedings, p 91

Figure 5. Electron microscopy image of silumin structure of eutectic composition subjected to electric explosion alloying; a – light field; b – dark field [111] Al + [112] YSi2; c – dark field [111] Si + [111] Y2Si2O7 (ring).