Nanostructurisation of hypoeutectic silumin by electroexplosion alloying and subsequent electron beam processing

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Abstract: The structure, phase composition and defect substructure of the surface layers of hypoeutectic silumin after the complex processing including the electroexplosion alloying (EEA) by the yttrium oxide powder and the subsequent electron beam processing have been analysed by the methods of modern physical materials science. The complex processing is accompanied by the dissolution of the silicon inclusions and intermetallides and the formation of the submicro- and nanodimensional structures. The modified layer (70 μm) is multielemental and it has the structure of high velocity cellular crystallisation.

Keywords: electroexplosion alloying; electron beams; hypoeutectic silumin; structure; phase composition.

Reference to this paper should be made as follows: Ivanov, Yu.F., Gromov, V.E., Zagulyaev, D.V., Konovalov, S.V., Rubannikova, Yu.A. and Semin, A.P. (2019) 'Nanostructurisation of hypoeutectic silumin by electroexplosion alloying and subsequent electron beam processing', *Int. J. Nanotechnol.*, Vol. 16, Nos. 6/7/8/9/10, pp.619–628.

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This paper is a revised and expanded version of a paper entitled 'The hypoeutectic silumin's structural phase state change on the electron-beam processing' presented at *X Conference of Nanotechnological Society of Russia*, Moscow, 26–28 March, 2019.

1 Introduction

Recently the attention of the researchers in the field of physical materials science is focused on the analysis of the nature of the surface hardening of metals and alloys under the effect of the concentrated fluxes of energy [1,2]. Among the widely distributed laser, plasma, ion and other types of effect the electroexplosion alloying (EEA) occupies a

special place. It possesses a number of advantages including those due to the formation of nanodimensional structural phase states at the pulsed regime of high-speed heating and cooling of the surface layer [3]. Under the EEA of the surface the refractory, heat- and corrosion resistant metals and alloys ensuring the high level of corresponding operational properties [3] can be used as the modified materials. The application of the rare-earth metals and their compounds [4–6] is of particular interest recently.

Nowadays, the promising method, from the positions of nanostructurisation, is the application of high intense pulsed electron beams of submillisecond duration. It makes possible to heat under control the surface layers tens of millimetres thick in the pulsed regime practically without changing in the structural phase state of the main volume of the material [7].

It is outlined in studies of Chinese researchers [8–10], that processing of eutectic and hypereutectic silumin by electron beams (pulse duration only some microseconds) (electron beam unit "Nadezhda-2", energy density ≤ 3 J/cm^2) results in the essential modification of properties in the material surface under the influence of dynamic stress fields generated on heating, melting and cooling. This modification is associated with the considerable refining of the structure, improvement of wear and corrosion resistance, and increase in hardness.

In our papers [11–13] the evolution of structural phase state of aluminium hypoeutectic alloy subjected to the irradiation in vacuum by the intense pulsed electron beam with the parameters increasing the listed in [8–10] was analysed. EEA with subsequent electron beam processing (EBP) results in the multiple increase in the wear resistance of the modified layer caused by the formation of multiphase submicro- and nanodimensional state [14,15].

The physical significance of the effect of nanodimensional structural phase states on the strength and plastic properties of the surface layer consists of the redistribution of the elastic energy due to the interaction of the elastic fields of the structural elements of various scale levels and due to the decrease in the scale level of plastic deformation localisation. It leads to the more uniform distribution of elastic stresses in the surface layer under the external mechanical and/or temperature effects. As a result, the energy necessary for the nucleation of the critical stress concentrators increases considerably, the essential decrease in the crack growth rate takes place, the hardness and plasticity of not only the surface layer but the sample, on the whole, increase [16,17].

The purpose of the research is to analyse the elemental and phase composition, the state of the defect structure of hypoeutectic silumin subjected to the complex processing combining the EEA and the subsequent irradiation by the intense pulsed electron beam.

2 Material and method

The hypoeutectic silumin AK10M2N [18] was used as a test material. The modification of silumin was done by the complex method. At the first stage the EEA [19] of samples by the yttrium oxide powder was carried out using the following regime: the aluminium foil mass – 58.9 mg; Y_2O_3 powder mass – 58.9 mg; the discharge voltage – 2.8 kW. At the second stage the alloyed surface of the samples was irradiated by the intense pulsed electron beam at the plant SOLO [20]. The following parameters of electron beam were used: the energy of the accelerated electron – 17 keV, the energy density of electron beam – 35 J/cm^2, the pulse duration – 150 μs, the number of pulses 3, the pulse repetition

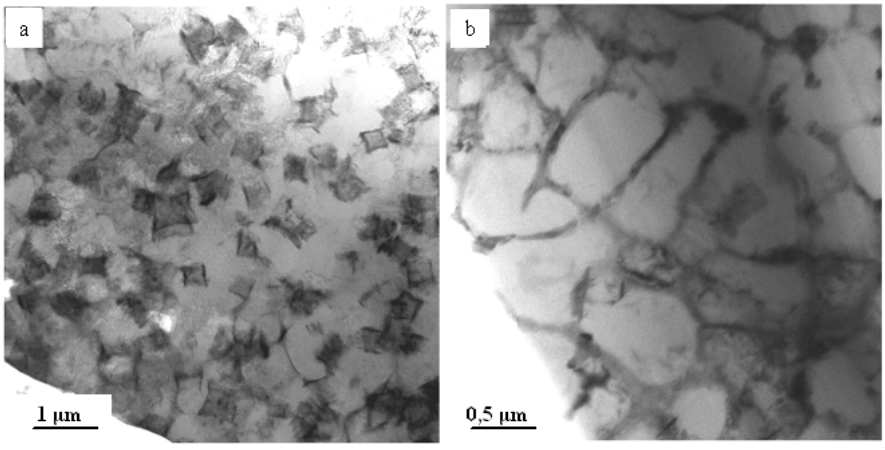
rate – 0.3 s^{-1}, the pressure of the residual gas (argon) in the working chamber of the plant – 2×10^{-2} Pa. The studies of the elemental and phase composition, the state of defect substructure were performed by the methods of scanning electron microscopy (device Philips SEM-515 with microanalyser EDAX ECON IV) and transmission electron diffraction microscopy (device JEM-2100F) [21–23].

3 Results and discussion

In the cast state the silumin structure is characterised by the presence of a large number of the inclusions of silicon and intermetallides of various shapes and submicron dimensions, the availability of pores revealed by the methods of optic and scanning electron microscopy. The complex processing of silumin including the EEA and subsequent irradiation by the intense pulsed electron beam results in the cardinal transformation of the structure of the samples' surface layer, the dissolution of the inclusions of silicon and intermetallides.

The application of the methods of transmission electron diffraction microscopy enabled to reveal the formation of the gradient submicro-nanodimensional structure in the modified layer, its characteristic image is shown in Figure 1.

Figure 1 Electron microscopic image of the structure of hypoeutectic silumin subjected to complex electron-ion-plasma processing: (a) surface layer structure and (b) structure of the layer located at the depth of 20–30 μm. Transmission electron diffraction microscopy



It is stated that the modified layer up to 70 μm thick has a structure of high velocity cellular crystallisation. The cell dimensions vary within 0.5–1.2 μm. The cells are separated by the interlayers of the second phase (Figure 1(b)). In the structure of the surface layer the inclusions of the faceted shape (Figure 1(a), the inclusions of dark colour) whose dimensions vary within 0.4–0.8 μm. The relative content of such inclusions decreases when moving away from the surface of modification.

The elemental composition of the modified layer was studied by the methods of micro-X-ray spectral analysis of thin foils. The energy spectra obtained from the surface

modified layer are shown in Figure 2. The quantitative analysis results of the elemental composition are presented in Table 1.

When analysing the results presented in Table 1, it can be noted that silumin surface layer is multi-elemental and along with the atoms of the initial material (aluminium, silicon, copper, nickel, chromium, iron) it is additionally enriched by the atoms of titanium, yttrium and oxygen.

Figure 2 Energy spectra obtained by the method of micro X-ray spectral analysis of silumin surface layer subjected to the complex processing (see online version for colours)

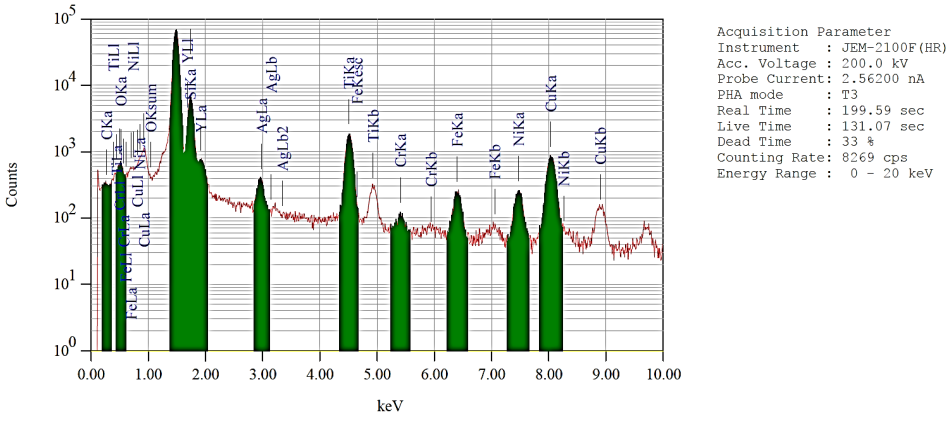


Table 1 Results of micro-X-ray spectral analysis of the elemental composition of silumin surface layer subjected to the complex processing

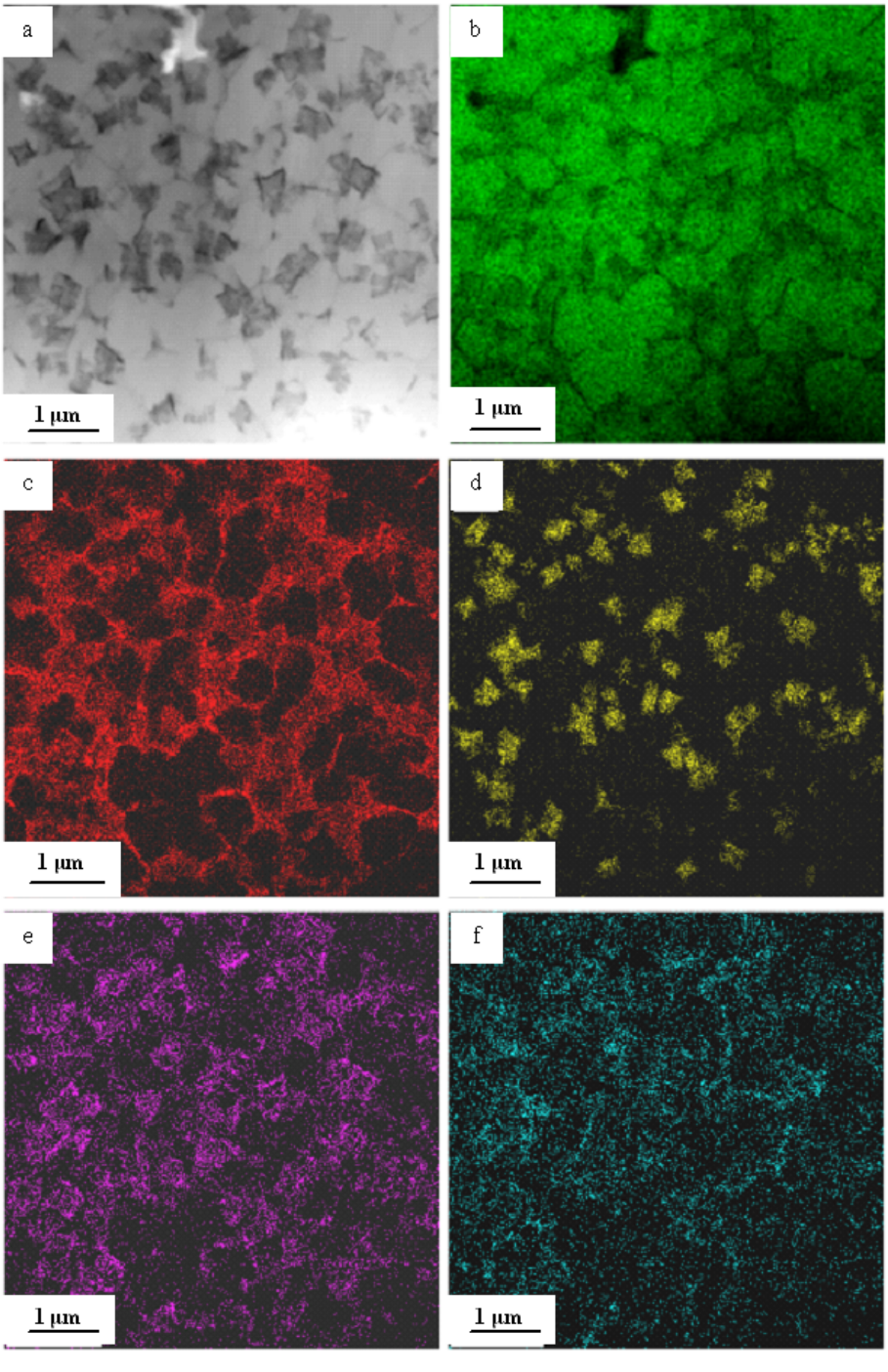
Thin Film Standardless Standardless Quantitative Analysis
Fitting Coefficient : 0.1562

Element		(keV)	Mass%	Counts	Error%	Atom%
C K						
O K		0.525	0.58	2635.55	0.43	1.04
Al K	(Ref.)	1.486	79.97	638973.88	0.00	85.77
Si K		1.739	7.29	60603.17	0.04	7.52
Ti K		4.508	3.77	23689.20	0.09	2.28
Cr K		5.411	0.11	640.12	3.62	0.06
Fe K		6.398	0.61	3193.95	0.68	0.32
Ni K		7.471	0.75	3484.12	0.69	0.37
Cu K		8.040	3.41	13998.93	0.18	1.55
Y L		1.922	2.64	5471.45	0.49	0.86
Ag L		2.984	0.88	1959.87	1.02	0.24
Total			100.00			100.00

The method of mapping [24] enables the analysis of the alloying elements in the material under study to be carried out. The results of mapping of the surface layer of the modified silumin are shown in Figure 3.

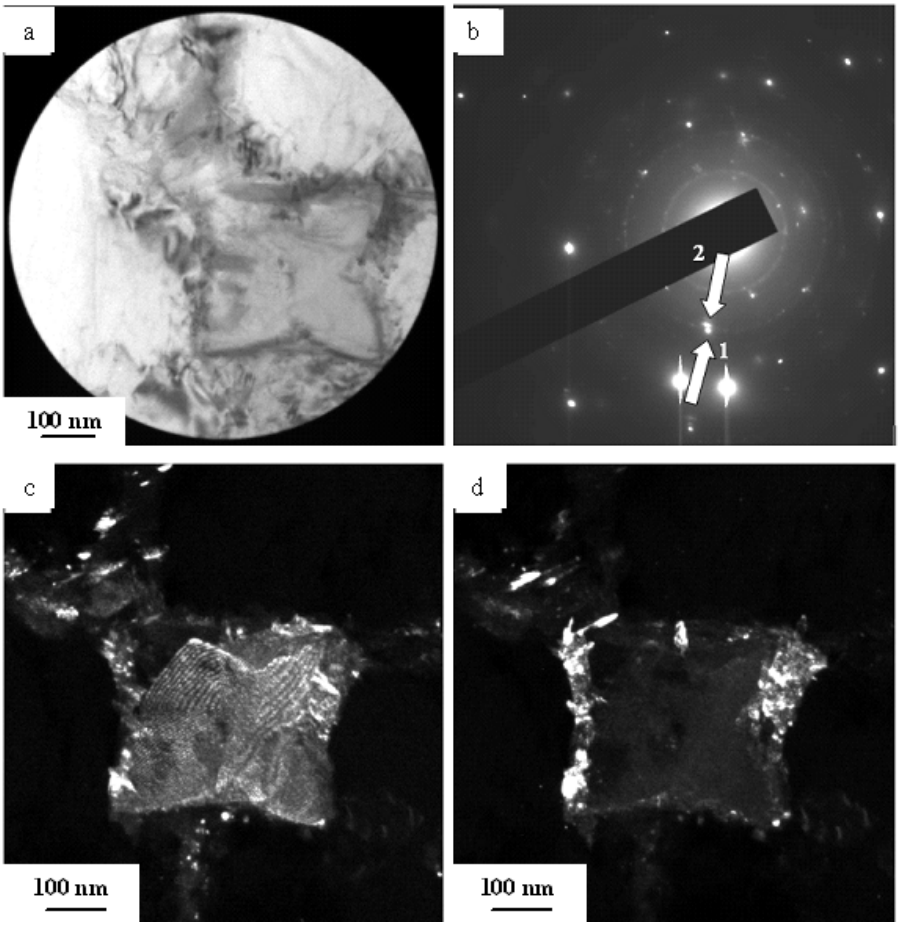
It is clearly seen that the cells of high-velocity crystallisation are enriched mostly by aluminium atoms (Figure 3(b)). The cells are separated by the interlayers enriched chiefly by silicon atoms (Figure 3(c)). The inclusions of the faceted shape (Figure 3(a), the inclusions of dark colour) are enriched mainly by the atoms of titanium, aluminium and copper (Figure 3(c), (d), (f)), the atoms of yttrium form principally the interlayers along the boundaries of the faceted shape inclusions (Figure 3(e)).

Figure 3 Electron microscopic image of the structure of silumin alloyed layer (a); the images (b–f) are obtained in the characteristic X-ray irradiation of aluminium (b), silicon (c), titanium (d), yttrium (e), and copper (f) atoms (see online version for colours)



The phase composition analysis of the surface layer of the modified silumin was performed using the method based on the obtaining of the dark-field images and the techniques of microelectron diffraction pattern indexing [25,26]. Figure 4 presents the results of the analysis of foil part containing the inclusions of the faceted shape.

Figure 4 Electron microscope image of the surface layer structure: (a) light field (the part of foil limited by the selection diaphragm); (b) microelectron diffraction pattern corresponding to the light field; (c) and (d) the dark fields obtained in the reflections [200] Al_5CuTi_2 and [300] AlCuY, respectively. In (b) the arrows designate the reflections in which the dark fields are obtained: 1 – c; 2 – d



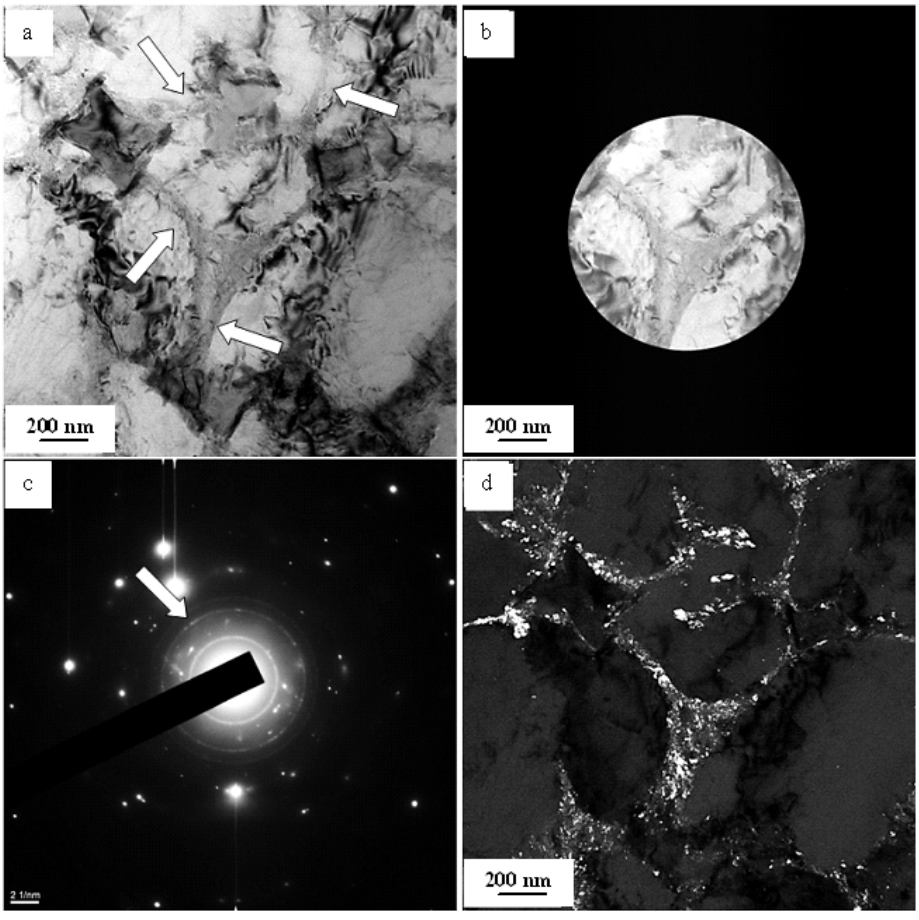
The performed electron microscopic microdiffraction analysis shows that the inclusions of the faceted shape are formed by the phase Al_5CuTi_2 (Figure 4(c)). Along the boundaries of these inclusions the interlayers having the phase composition of AlCuY (Figure 4(d)) are found.

Figure 5 shows the characteristic image of the structure of silumin cellular crystallisation.

The microelectron diffraction pattern obtained from the given part of foil contains the separately located point reflections and the reflections forming the rings (Figure 5(c)).

The indexing of the microelectron diffraction pattern showed that the reflections forming the diffraction rings belong to the crystal lattice of silicon. The dark-field image of the structure of silumin surface layer obtained in the refractions of diffraction ring (Figure 5(c), the reflection is designated by the arrow) is shown in Figure 5(d). When analysing the results presented in Figure 5(d) one may note that the silicon interlayers being located along the boundaries and in the boundary junctions of the crystallisation cells formed by the solid solution based on aluminium have a nanocrystalline structure with the size of crystallites varying within 10–20 nm.

Figure 5 Electron microscope image of the structure of silumin surface layer subjected to the complex processing; (a) and (b) light fields; (c) microelectron diffraction pattern obtained from the foil part limited by the selection diaphragm (the image of the part is shown in (b) and (d) dark field obtained in the reflection [220] Si designated by the arrow in (c). The arrows designate the silicon interlayers (a)



4 Conclusion

The complex processing of the surface of hypoeutectic silumin AK10M2N combining the EEA and the subsequent irradiation by the intense pulsed electron beam has been performed. The cardinal transformation of the structure of the material's surface layer ≈ 70 μm thick consisting of the dissolution of silicon inclusions and intermetallides of micron and submicron dimensions characteristic of the cast silumin and the formation of the gradient multielemental submicro-nanodimensional structure has been revealed. It has been found that the modified layer has the structure of the high-velocity cellular crystallisation and contains the inclusions of the faceted shape whose relative content decreases when moving away from the surface of modification. It has been shown by the methods of micro-X-ray spectral analysis that the surface layer of silumin is a multi-elemental one and along with the atoms of the initial material (aluminium, silicon, copper, nickel, chromium, iron) it is additionally enriched by the atoms of titanium, yttrium and oxygen. It has been established that the cells of high velocity crystallisation are enriched by aluminium atoms and the interlayers separating the cells are enriched by silicon atoms. The inclusions of the faceted shape are enriched by the atoms of titanium, aluminium and copper and the interlayers along the boundaries of the inclusions contain, mainly, the yttrium atoms. It has been revealed that the interlayers of silicon located along the boundaries and in the junctions of the boundaries of the crystallisation cells formed by the solid solution based on aluminium have a nanocrystalline structure with the crystallite dimensions varying within 10–20 nm.

Acknowledgements

The research was financially supported by the State assignment of the Ministry of Science RF (project № 3.1283.2017/4.6) and RFFI grant (project № 19-48-700010).

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