Nanostructure formation of hypoeutectic silumin by electron-ion-plasma methods

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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 ion plasma alloying by the yttrium oxide powder and the subsequent electron beam processing have been analyzed by the methods of modern physical material science. The complex processing is accompanied by the dissolution of the silicon inclusions and intermetallics and the formation of the submicro- and nanodimensional structure. The modified layer (70 μm) is multielemental and it has the structure of high velocity cellular crystallization.

1. Introduction

Recently the attention of the researchers in the field of physical material 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 different widely distributed types of effect the electroexplosion ion plasma alloying (EIPA) 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].

Nowadays, the promising method, from the positions of nanostructurization, is the application of high intense pulsed electron beams of submillisecond duration. It makes possible to heat under control the surface layers tens micrometers thick in the pulsed regime practically without changing in the structural phase state of the main volume of the material [4].

It is outlined in studies of Chinese researchers [5–7], that processing of eutectic and hypereutectic silumin by electron beams (pulse duration only some microseconds) (electron beam unit «Nadezhda-2», energy density ≤ 3 J·cm²) 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 [8–10] 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 [5–7] was analyzed. EIPA 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 [11, 12].

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

2. Material and method

The hypoeutectic silumin AK10M2N [13] was used as a test material. The modification of silumin was done by the complex method. At the first stage the electroexplosion ion plasma alloying [14] of samples by the yttrium oxide powder was carried out using the following regime: the aluminium foil mass – 58.9 mg; Y₂O₃ powder mass – 58.9 mg; the discharge voltage – 2.8 kV. At the second stage the alloyed surface of the samples was irradiated by the intense pulsed electron beam at the plant SOLO [15]. 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 microanalyzer EDAX ECON IV) and transmission electron diffraction microscopy (device JEM-2100F) [16–18].

3. Results and discussion

In the cast state the silumin structure is characterized by the presence of a large number of the inclusions of silicon and intermetallics 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 electroexplosion ion plasma alloying 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 intermetallics.

It was stated that the modified layer up to 70 μm thick has a structure of high velocity cellular crystallization. The cell dimensions vary within 0.5–1.2 μm. The cells are separated by the interlayers of the second phase. In the structure of the surface layer the inclusions of the faceted shape whose dimensions vary within 0.4–0.8 μm are present. The relative content of such inclusions decreases when moving away from the surface of modification.

Method of mapping [19] enables to carry out the analysis of alloying elements distribution. It was established that the cells of high-velocity crystallization are enriched mostly by aluminium atoms. The cells are separated by the interlayers enriched chiefly by silicon atoms. The inclusions of the faceted shape are enriched mainly by the atoms of titanium, aluminium and copper, the atoms of yttrium form principally the interlayers along the boundaries of the faceted shape inclusions.

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 [20, 21]. Figure 1 presents the results of the analysis of foil part containing the inclusions of the faceted shape.

The performed electron – microscopic microdiffraction analysis shows that the inclusions of the faceted shape are formed by the phase Al₅CuTi₂ (figure 1c). Along the boundaries of these inclusions the interlayers having the phase composition of AlCuY (figure 1d) are found.

Figure 2 shows the characteristic image of the structure of silumin cellular crystallization.

The microelectron diffraction pattern obtained from the given part of foil contains the separately located point reflections and the reflections forming the rings (figure 2c). 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 reflections of diffraction ring (figure 2c, the reflection is designated by the arrow) is shown in
figure 2d. When analyzing the results presented in figure 2d one may note that the silicon interlayers being located along the boundaries and in the boundary junctions of the crystallization cells formed by the solid solution based on aluminium have a nanocrystalline structure with the size of crystallites varying within 10–20 nm.

Figure 1. 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, d – the dark fields obtained in the reflections [200] Al₃CuTi₂ and [300] AlCuY, reflectively. In (b) the arrows designate the respective in which the dark fields are obtained: 1 – c; 2 – d.
4. Conclusion
The complex processing of the surface of hypoeutectic silumin AK10M2N combining the electroexplosion ion plasma alloying 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 in 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 crystallization 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 crystallization 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 crystallization 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 of the Russian Federation (project No. 3.1283.2017/4.6) and RFBR grant (project No. 19-48-70010).

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