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Modification of the sample's surface of hypereutectic silumin by pulsed electron beam

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Abstract. The article presents the results of the analysis of the elemental and phase composition, defect substructures. It demonstrates strength and tribological characteristics of the aluminium-silicon alloy of the hypereutectic composition in the cast state and after irradiation with a high-intensity pulsed electron beam of a submillisecond exposure duration (a Solo installation, Institute of High Current Electrons of the Siberian Branch of the Russian Academy of Sciences). The research has been conducted using optical and scanning electron microscopy, and the X-ray phase analysis. Mechanical properties have been characterized by microhardness, tribological properties – by wear resistance and the friction coefficient value. Irradiation of silumin with the high-intensity pulsed electron beam has led to the modification of the surface layer up to 1000 microns thick. The surface layer with the thickness of up to 100 microns is characterized by melting of all phases present in the alloy; subsequent high-speed crystallization leads to the formation of a submicro- and nanocrystalline structure in this layer. The hardness of the modified layer decreases with the increasing distance from the surface exposure. The hardness of the surface layer is more than twice the hardness of cast silumin. Durability of silumin treated with a high intensity electron beam is ≈1,2 times as much as the wear resistance of the cast material.

1. Introduction

The application of hypereutectic silumin is limited due to its structure instability conditioned by, in particular, its uneven distribution in the castings of relatively large crystals of primary silicon and intermetallic inclusions. Segregation of primary silicon crystals in hypereutectic silumin leads to worsening of castings cutting, anisotropy of the alloy properties in the cross section of castings, a relatively low level of mechanical properties and, first of all, ductility, wear resistance reduction of products. In order to suppress primary crystallization of a silicon phase it is proposed:

- to overheat the melt above the dome of collapse of the metastable colloid thus obtaining quasi-eutectic [1].
- to use vibration [2], melt processing by a periodic (cyclic) pulse unipolar electric current [3] and other energetic effects on the melt [4].

In [5] it is offered to provide a combination of the high crystallization rate of the alloy, a modification with phosphorus, and additional heat treatment, in case of obtainment of castings for subsequent plastic deformation, to produce the high quality castings of hypereutectic silumin, containing fine, less than 15 microns, crystals, which are uniformly distributed in the volume of the primary silicon.

The purpose of this paper is to analyze the results obtained in the study of structure and properties of the surface layer of the composition of hypereutectic silumin irradiated with a high-intensity pulsed electron beam of a submillisecond exposure duration.

2. A Material and a Research Technique

A material for the study was samples of the aluminum-silicon alloy (silumin) of the hypereutectic composition. The average concentration of silicon amounts to 28.5 wt. % (the concentration of silicon in the range of 22.1…35.5 wt. %). The concentration of silicon was measured by the electron microprobe analysis of cast samples (averaging according to the results of the elemental analysis of five areas with sizes of 1,2x0,95 $mm^{2)}$.

The samples surface was modified by the high-intensity pulsed electron beam on the 'Solo' installation (Institute of High Current Electronics, the Siberian Branch of the Russian Academy of Sciences) [6]; the energy density of the electron beam is 40 J/cm^2, pulse repetition frequency is 0.3 Hz, the number of pulses were 20; the electron beam pulse duration is 200 μs, and the energy of accelerated electrons is 18 keV. The study of the elemental and phase composition, a defect structure of the modification surface and transverse sections was performed by the methods of optical and scanning electron microscopy, and the X-ray analysis. Mechanical properties of the material were characterized by microhardness. The study of the silumin wear resistance was conducted in the geometry of disc-pin at room temperature and humidity (a CSEM pin-on-disk tribometer, Switzerland). The volume of the material wear-and-tear was estimated after conducting a profilometry of the formed track (a MicroMeasure 3D Station, Stil, France).

3. Research Results and Discussion

Silumin in its original state is a very nonhomogeneous material. The analysis of the structure of the section, realized by the methods of scanning electron microscopy, has allowed one to reveal rough inclusions of silicon and intermetallic compounds. Their average sizes may reach 50 microns (Figure 1). The inclusions have different shapes; they are distributed in the volume of the material unevenly. Melting of samples was accompanied by the formation of many micropores in the volume of material in a chaotic manner (Figure 1).

The electron microprobe analysis of the original sample (averaging according to the results of the elemental analysis from five areas with the sizes of 1.2×0.95 mm^2) has revealed a silicon concentration of 28.5 wt. % (when changing the silicon concentration in the range of 22.1…35.5 wt. %). Investigations of the phase composition of the original alloy have revealed the presence of the two main phases – a solid solution based on alumina and a solid solution based on silicon – in the material. The research was carried out with the methods of X-ray diffraction. The X-ray pattern of the original sample has shown weak lines obviously belonging to intermetallic compounds. The X-ray pattern analysis showed that these intermetallic compounds are the phases of Al_9FeSi_3 or $FeAl_3Si_2$ compositions. The results of X-ray phase analysis of the main phases structure of the studied alloy have showed that initially the parameters of aluminum and silicon lattices are close to the tabulated values; the dimensions of the areas of coherent aluminum scattering are significantly greater than those of silicon.

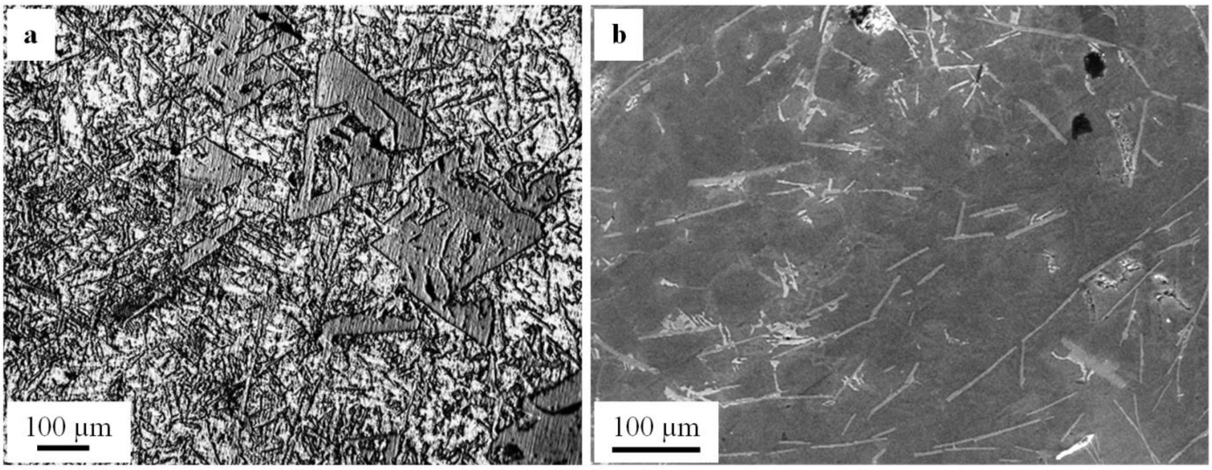

Figure 1. A structure of the cast silumin sample prior to irradiation with the high-intensity pulsed electron beam: *a* – optical microscopy; *b* – scanning electron microscopy.

The samples of the aluminum-silicon alloy were irradiated, as previously performed calculations of the temperature field showed [7-9], in the melting mode of all present in the material phases. Figure 2a shows micrographs demonstrating the sample surface structure being treated with an electron beam. It is clearly seen that a homogeneous layer forms along with the structure of the high-speed crystallization. The crystallite sizes vary in the ranges of 0.4...0.5 microns. The microprobe analysis indicates that the silicon concentration in the surface layer varies in the ranges of 10...12 at. %. It. corresponds to the composition of the aluminum-silicon alloy eutectic [10].

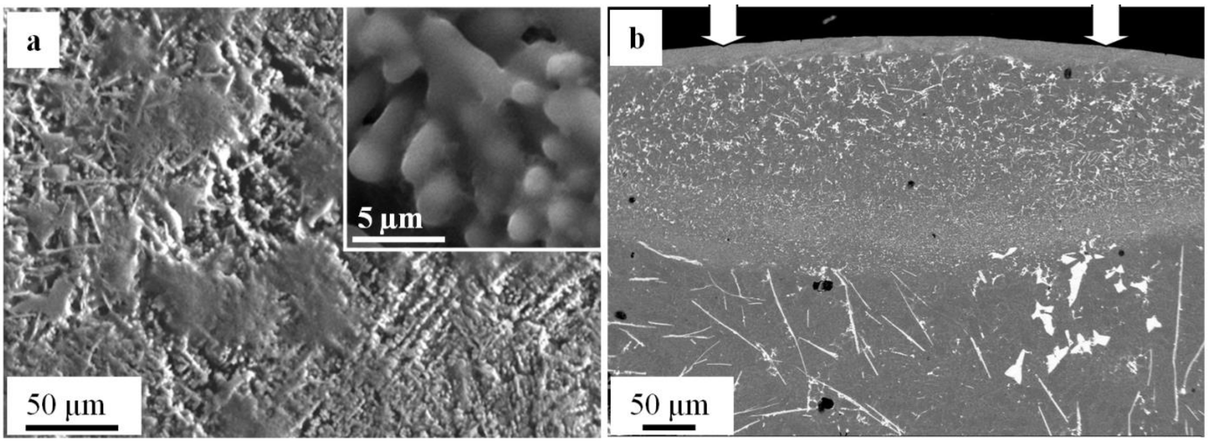

Figure 2. An electron microscope image of the surface structure (a) and a transverse section (b) of silumin, irradiated with the high-intensity pulsed electron beam. In (b) the arrows indicate the surface of radiation exposure.

The X-ray phase analysis of the modified sample has showed that the influence of the electron beam leads to a significant reduction in the sizes of coherent scattering regions (OCD) of both aluminum and silicon. The parameter of the crystal lattice of aluminum and silicon increases. The increase of the parameters of the aluminum and silicon lattice is probably due to dissolution of impurity atoms (Mg, Fe, Cu) in them. This assumption is confirmed by the absence of diffraction lines of the corresponding intermetallic phases on the X-ray patterns of the irradiated samples.

The analysis of the structure of the transverse section irradiated by the electron beam has revealed the formation of a multi-layer structure (Figure 2b), such as:

- a surface layer (Figure 3a) formed as a result of melting and speed crystallization of all phases of the material (aluminum, silicon and intermetallic precipitates);

- an intermediate layer (Figure 3b) containing not completely dissolved, particularly large inclusions of silicon and intermetallic compounds;
- a transition layer (Figure. 3c) containing not completely dissolved inclusions of silicon and intermetallic compounds.

The total thickness of the modified layer is up to 1000 microns. A silumin layer modified by the electron beam becomes dense and comprises a minimum number of micropores and microcracks. This result can serve as a recommendation to irradiate silumin with the high-intensity pulsed electron beam as a method, which enables one to remove micropores and microcracks formed in the process of material melting from a relatively thick surface layer.

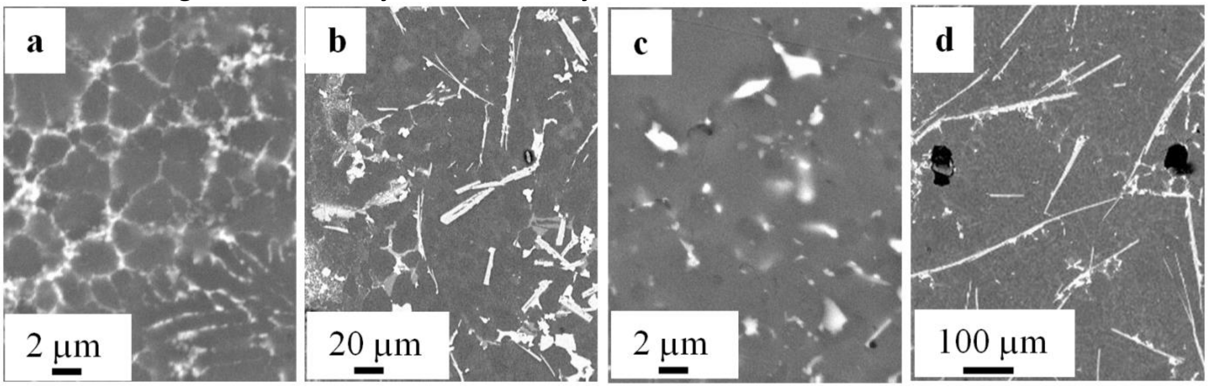

Figure 3. A silumin volume structure modified by the electron beam: *a* – a surface layer; *b* – an intermediate layer; *c* – a transition layer; *d* – the bulk of the material. Scanning electron microscopy of the cross etched polished section

The structure of the surface layer, which has been formed as a result of high-speed crystallization, is represented by crystallites (obviously, a solid solution based on aluminum) surrounded by relatively thin interlayers of the second phase (obviously, silicon and, possibly, intermetallics) (Figure 3a). The crystallite sizes vary within the limits of 2 microns to 5 microns. The transverse dimensions of interlayers amount to a few tenths of a micrometer. The thickness of the surface layer reaches 100 microns. The intermediate layer is characterized by the presence of a large number of intermetallic inclusions, which number exceeds the similar characteristic of the original material per unit of the section surface (Figure 3b). This fact allows one to suggest that the intermediate layer has been enriched with the intermetallic phase previously located in the surface layer and transferred to the intermediate layer under the action of gravity forces, when melting the material by the electron beam. The thickness of the intermediate layer reaches 400 microns. The transition layer is the longest one, its thickness reaches 500 microns. This layer is characterized by the presence of relatively fine silicon inclusions, predominantly of a globular shape, and intermetallic compounds, which sizes are 2…5 microns. These sizes are significantly less than the sizes of the inclusions disposed in the intermediate layer and in the bulk of the material (Figure 3c).

The mechanical properties of silumin were characterized by the microhardness value. The accomplished studies have shown that irradiation of silumin with the high-intensity pulsed electron beam in the mode of melting of the surface layer leads to the formation of the multilayer structure. Its hardness naturally decreases when it is distant from the surface of treatment. After treatment with the electron beam the microhardness of the surface of irradiation is ≈1.9 GPa; the hardness of the surface layer of the silumin modified by the electron beam is ≈1.60 GPa, the hardness of the intermediate layer is ≈1.08 GPa, the hardness of the transition layer – ≈0.97 GPa. The microhardness value of the original material is ≈0.8 GPa. The microhardness of the surface of irradiation exceeds the microhardness of the original material more than 2 times.

It has been found that the wear resistance of silumin treated by the high-intensity electron beam is ≈1.2 times greater than that of the cast material; the friction coefficient of irradiated silumin is ≈1.5 times less than that of the cast material.

4. Conclusion

The results of the analysis of the elemental and phase composition, the defect substructure, strength and tribological characteristics of the hypereutectic silumin composition in the cast state and after irradiation with the high-intensity pulsed electron beam of a submillisecond exposure duration (a SOLO installation, Institute of High Current Electronics, the Siberian Branch of the Russian Academy of Sciences) have been represented.

The studies have been performed by using optical and scanning electron microscopy and X-ray diffraction. Mechanical properties were characterized by microhardness, tribological properties – by resistance to wear and friction coefficient. A characteristic feature of the alloy in the cast state is the presence of a big number of large (up to 50 micrometers in diameter) particles of excess silicon, intermetallic inclusions (Al_9FeSi_3 or $FeAl_3Si_2$) and micropores. Irradiation of silumin by the electron beam has resulted in the modification of the surface layer up to 1000 microns. The modified volume has a multilayer structure devoid of micropores and microcracks. The surface layer with the thickness of up to 100 microns is characterized by melting of all phases present in the alloy. In this layer high-speed crystallization leads to formation of the submicro- and nanocrystalline structure. Underlying sublayers contain both insoluble inclusions of initial phases and compounds formed during high-speed crystallization and cooling of the material. The hardness of the surface layer is more than two times greater than the hardness of cast silumin. When moving away from the irradiated surface, the hardness of the modified layer naturally reduces. The wear resistance of silumin, treated with the high intensity electron beam, is ≈1,2 greater than the wear resistance of the cast material in 2 times. The friction coefficient of irradiated silumin is 1,5 times less than that of the cast material.

Acknowledgments

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