Thermal stability of the hypereutectic silumin structure subjected to a pulsed electron beam treatment

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Abstract. Hypereutectic silumins have many positive properties - low density, high specific strength and corrosion resistance. They are non-magnetic, retain their strength at low, up to cryogenic temperatures, have a relatively low thermal expansion coefficient, high modulus of elasticity, increased wear resistance in friction pairs, etc. The structure of hypereutectic silumin is formed by a plastic eutectic matrix and brittle primary silicon crystals larger than 100 μm, and also contains crystals of aluminides of iron, copper, titanium and zirconium. Silumin of hypereutectic (18 wt% Si) composition was modified by irradiating the specimens by an intense pulsed electron beam. It was found that irradiation of hypereutectic silumin with an electron beam leads to a significant decrease in the number of micropores, the formation of a structure of high-speed cellular crystallization.

1. Introduction
In the manufacture of ingots and shaped castings from silumins [1–5] in the industry, modification of the melt is the obligatory operation, which is associated with the presence in the structure of silumins of rather large precipitates of eutectic and primary silicon, the sizes of which depend on the composition of alloys and their production technology [6, 7].

Castings with sizes of primary silicon crystals less than 100 μm was formed by traditional methods of modifying the hypereutectic silumins structure and grinding primary silicon crystals by introducing small additions of phosphorus (<0.1%) into the charge. This made it possible to obtain material with satisfactory plasticity (<2.0%), however, such plasticity is not enough for the formation of ingots by continuous casting [5].

A method of obtaining a piston blank from granules obtained under conditions of high cooling rate during crystallization is known [8]. Depending on the size of the granules and the cooling conditions, the primary silicon crystals are crushed to (3–20) microns, uniformly located in the alloy matrix, providing high mechanical properties and good wear resistance. The disadvantage of the method of obtaining a pressed piston billet by the granular metallurgy method is the multi-operation and high labor intensity of the technological process of obtaining a bar-billet.

Less laborious is the method of producing piston blanks from hypereutectic silumin, which consists in casting the alloy into a metal chill mold from a holding furnace [9]. To grind large crystals of primary silicon before pouring the melt into the chill mold, ligatures or salts with phosphorus compounds are introduced into the holding furnace, which, after holding in the melt, contribute to the grinding of primary silicon crystals to 30-50 μm [10, 11].
The disadvantage of this technology is the low strength and plasticity of the cast structure of the resulting blank. A more effective technology for modifying silumin alloys is out-of-furnace modification, in which a rod of a master alloy containing dispersed aluminides of transition metal phases is introduced into a stream of the alloy being poured. This provides a more efficient refinement of the grain structure [12].

One of the promising methods for modifying the structure and properties of silumin is their surface treatment with an intense pulsed electron beam, which results in a significant increase in the mechanical, tribological, and fatigue properties of the material [13, 14].

The aim of this work is to discover regularities in the transformation of the structure and properties of the hypereutectic silumin surface layer as a result of irradiation with an intense pulsed electron beam.

2. Material and methods
Specimens of the Al-18% Si alloy, which is the object of the study, had the form of plates with dimensions of 15x15x5 mm. The surface treatment of the samples was carried out on the «SOLO» setup, which allows generating electron beams in a pulsed mode with the following characteristics: the energy of accelerated electrons up to \( U = 25 \text{ keV} \), the energy density of the electron beam up to \( ES = 80 \text{ J/cm}^2 \), the electron beam pulse duration \( \tau = (30-200) \mu\text{s} \), pulse repetition rate up to \( f = 15 \text{ s}^{-1} \), residual pressure of the working gas in the chamber \((0.02-0.03) \text{ Pa}\) [13]. Silumin specimens were processed with an electron beam with parameters \( 18 \text{ keV}, (10-40) \text{ J/cm}^2, 200 \mu\text{s}, 3 \text{ imp.,} 0.3 \text{ s}^{-1}, \text{ working gas pressure (argon) 0.02 Pa.} \) The thermal stability of the modified silumin specimens structure was studied under annealing conditions at 473 K and 673 K (2 and 4 hours) in an argon atmosphere at a residual pressure of 0.1 Pa. Studies of the structure and phase composition of silumin were carried out by optical, scanning, and transmission electron microscopy. The properties of the surface layer were characterized by microhardness (device PMT-3, load on the indenter 0.5 N and 0.3 N) and wear resistance.

Tribological tests of irradiated silumin specimens were carried out under dry friction conditions according to the "disk - pin" scheme on a Pin on Disc and Oscillating TRIBOtester (TRIBOtechnic, France) with the following parameters: a ball made of VK8 hard alloy 6 mm in diameter, track diameter 4 mm, speed rotation \(2.5 \text{ cm/s}, \text{ load } 5 \text{ N}, \text{ distance to stop } 200 \text{ m}. \) Wear resistance of the surface layer was calculated after the formed track profilometry.

3. Results and discussion
The investigated silumin in the cast state is characterized by the presence of micropores, inclusions of various shapes and sizes (figure 1, a). Irradiation of silumin by a pulsed electron beam with an energy density of \(10 \text{ J/cm}^2\) leads to insignificant surface melting, as a result of that no dissolution of silicon crystallites and intermetallic compounds is observed, and a large number of micropores are still recorded.

Figure 1. Structure of hypereutectic silumin in the cast state (a) and after irradiation with a pulsed electron beam (25 J/cm2, 200 μs, 3 pulses) (b, c). Scanning Electron Microscopy.
The treatment of silumin by an electron beam with an energy density of 25 J/cm² and higher is accompanied by melting and subsequent high-speed crystallization of the surface layer. A dispersed structure is formed in the surface layer, micropores and microcracks are melt (figure 1, b, c).

Using the methods of diffraction electron microscopy of "transverse" foils (foils were made by thinning the plates cut from the analyzed specimen in a section perpendicular to the irradiation surface), it was found that a structure of high-speed cellular crystallization is formed in the surface layer (40-60) microns thick after pulsed electron beam treatment with an energy density of (25-40) J/cm² (figure 2, a). Micro X-ray spectral analysis showed that the volume of cells is formed by a solid solution based on aluminum. Silicon is located in the form of interlayers along the boundaries of aluminum cells, and also forms globular inclusions located randomly in the modified silumin surface layer (figure 2, b). It was found that the average cell size increases from 290 nm to 500 nm with an increase in the energy density of the electron beam in the range (25-40) J/cm².

Figure 2. The structure of the silumin surface layer of specimen irradiated with an electron beam with parameters 25 J/cm², 200 μs, 3 pulses; a - STEM image; b - an image obtained in the characteristic X-ray radiation of silicon atoms. The arrows indicate the electron beam irradiation surface.

Figure 3. Structure of silumin irradiated with an electron beam with parameters 25 J/cm², 200 μs, 3 pulses and subjected to annealing at a temperature of 473 K, 2 hours; a - bright field, b - dark field obtained in the [111] Si reflection, c - microelectron diffraction pattern. The arrow on (c) indicates the reflex in which the dark field was obtained. Transmission electron microscopy.
At the same time, the transverse dimensions of the second phase interlayers also increase from 80 nm to 110 nm. The sizes of globular silicon inclusions vary from 0.5 microns to 1.3 microns. Mechanical and tribological tests were performed. It is shown that in the best case (25 J / cm², 200 µs, 3 pulses), the microhardness of the surface layer 45 µm thick increases 1.4 times relative to the initial state; wear resistance increased by 7.8 times, friction coefficient decreased by 1.8 times.

![Figure 4](image)

**Figure 4.** Structure of the silumin surface layer irradiated with an electron beam with parameters 25 J / cm², 200 µs, 3 pulses and subjected to annealing at a temperature of 673 K, 4 hours; a - STEM image; b - d - images obtained in characteristic X-ray radiation of silicon, iron and nickel atoms, respectively.

The thermal stability of the modified silumin specimens structure was studied under annealing conditions at the temperatures of 473 K and 673 K (2 and 4 hours) in an argon atmosphere at a residual pressure of 0.1 Pa. We used specimens pre-treated with a pulsed electron beam (25 J / cm², 200 µs, 3 pulses), which showed the highest values of microhardness and wear resistance. As a result of the performed studies, it was found that holding the specimens of hypereutectic silumin irradiated with a pulsed electron beam at a temperature of 473 K for 2 and 4 hours does not lead to the destruction of the structure of high-speed cellular crystallization and promotes the decomposition of a solid solution based on aluminum with the formation in the volume of cells silicon nanosized particles and intermetallic compounds (figure 3). The microhardness of silumin subjected to irradiation and subsequent annealing at a temperature of 473 K for 2 and 4 hours increased 2 times relative to the cast state; wear resistance is 1.9 times higher than that of cast silumin.
Exposure of silumin samples irradiated by a pulsed electron beam at a temperature of 673 K for 4 hours led to a partial destruction of the cellular crystallization structure, as well as an increase in the size of the second phase particles located at the cell boundaries (figure 4). Attention is drawn to the fact that, under annealing conditions, silicon inclusions are predominantly globular, the sizes of that vary from 0.2 μm to 1.3 μm (figure 4, b).

An increase in the annealing temperature to 673 K (4 hours) led to the formation of a surface layer, the microhardness of which exceeds the microhardness of cast silumin by 1.4 times, wear resistance by 7.7 times. Comparison of the results obtained during mechanical and tribological tests, it can be noted that annealing of specimens of hypereutectic silumin at a temperature of 673 K, 4 hours exposed to irradiation with a pulsed electron beam (25 J/cm², 200 μs, 3 pulses) does not lead to an decrease of the microhardness and wear resistance of the material.

4. Conclusions
The performed studies, the results of that are presented in this work, made it possible to reveal the mode of silumin irradiation by an intense pulsed electron beam (25 J/cm², 200 μs, 3 pulses), which leads to the formation in the surface layer up to 50 μm thick of a multiphase submicro-nanocrystalline structures, the microhardness and wear resistance of that are exceeded 1.4 times and 7.8 times the corresponding characteristics of silumin in the cast state. Additional heat treatment of irradiated specimens of hypereutectic silumin at a temperature of 673 K for 4 hours does not lead to a decrease in the microhardness and wear resistance of the material.

Acknowledgments
The study was carried out with the financial support of the Russian Foundation for Basic Research (project No. 19-52-04009 and project project No. 20-58-00006 Bel_a).

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