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# STRENGTH CHARACTERISTICS OF HYPEREUTECTIC SILUMIN AFTER ELECTRON BEAM MODIFICATION

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*Irradiation (SOLO installation, Institute of High Current Electronics, Siberian Branch of the Russian Academy of Sciences) of hypereutectic silumin specimens of Al–(22–24)Si composition with an intense pulsed electron beam was carried out. The formation of the structure of high-speed cellular crystallization of aluminum (cell size 250–600 nm) was revealed. It was shown that the cell boundaries are strengthened by globular-shaped silicon particles (particles of size 50–70 nm). It was found that the hardness of the silumin specimen surface layer increases by more than 5 times after modification. Tensile tests of plane proportional samples showed an increase in the ductility of irradiated samples while maintaining the tensile strength.*

**KEY WORDS:** *aluminum, silicon, surface, properties, hardening, structure, additive technologies, mechanical engineering*

## 1. INTRODUCTION

Hypereutectic silumin is an alloy of aluminum with silicon. This alloy is widely used in the manufacture of machine parts and devices. The surface of the alloy is covered with oxide film. The solubility of aluminum in silicon is close to zero. The constitution diagram of the alloy has a simple eutectic form (Gavrilin et al., 2003; Hansen and Anderko, 1965). The percentage of silicon distinguishes between hypoeutectic (Si < 11%), eutectic (Si = 11–12.5%), and hypereutectic (Si > 12.5%) silumins (Belov et al., 2007). Hypereutectic silumin consists of aluminum grains, primary silicon grains, eutectic grains, inclusions of intermetallic compounds based on aluminum, silicon, iron, copper, and manganese. A specialty of the hypereutectic silumin is that when the melt is placed in the mold, hydrogen is adsorbed. Therefore, pores and shells form in the cast billet (Kolachev, 1966). This phenomenon affects the diffusion of silicon. Modification of silumins by an electron beam leads to the formation of a multilayer nonequilibrium submicro-nanocrystalline structure in the surface layer, the thickness of which, depending on the parameters of the electron beam, can reach 1 mm (Rygina et al., 2016).

The aim of this work is to study the structure and mechanical properties of a hypereutectic silumin after a submillisecond exposure duration pulsed electron beam modification.

## 2. MATERIAL AND EXPERIMENTAL TECHNIQUE

Specimens of hypereutectic silumin with 22–24 wt.% silicon concentration were used as the research material. The blades for tensile testing in accordance with the State Standard GOST 1497-84 (Matorin et al., 2005) were prepared. Before the tests, some of the specimens were irradiated with an intense pulsed electron beam [SOLO setup (Koval and Ivanov, 2008)]. The irradiation mode consisted of accelerated electron energy 18 keV, electron beam energy density 15–50 J/cm$^2$, pulse repetition rate 0.3 s$^{-1}$, exposure time of the electron beam 150 μs, number of irradiation pulses 5. The irradiation mode was selected according to thermal calculations (Ivanov et al., 2015). Samples were studied by optical (μVizo-MET-221) and scanning electron (SEM-515 Philips) microscopes. Hardness tests were carried out on the PMT-3 device. Tensile tests to failure were carried out on an Instron 3369 machine.

## 3. RESULTS AND DISCUSSION

The initial structure of the hypereutectic silumin consisted of eutectic, primary silicon grains, as well as intermetallic compounds (Fig. 1a). The presence of silicon primary grains and intermetallic compounds, as well as micropores, is the main reason for the low ductility and high brittleness of the material.

The study of the cross-sectional structure of the hypereutectic silumin showed that with an irradiation regime of 50 J/cm$^2$, 150 μs, 0.3 s$^{-1}$, 5 pulses the thickness of the modified surface layer is 100–120 μm. In the surface layer during processing, nonequilibrium structures of the micro- and nanoscale range are formed (Fig. 2), the crystallite size is 2–4 μm.

Energy dispersive x-ray analysis showed the presence of aluminum, silicon (23.3 wt.%), atoms in the composition of silumin, and iron impurities – 1.7 wt.% (Fig. 3). After silumin irradiation (50 J/cm$^2$, 150 μs, 0.3 s$^{-1}$, 5 pulses), as shown in Figs. 2 and 3a, in the surface layer there are no primary silicon grains and intermetallic compounds that correspond to the cast state. This indicates a remelting of the silumin surface layer with complete dissolution of all the phases.

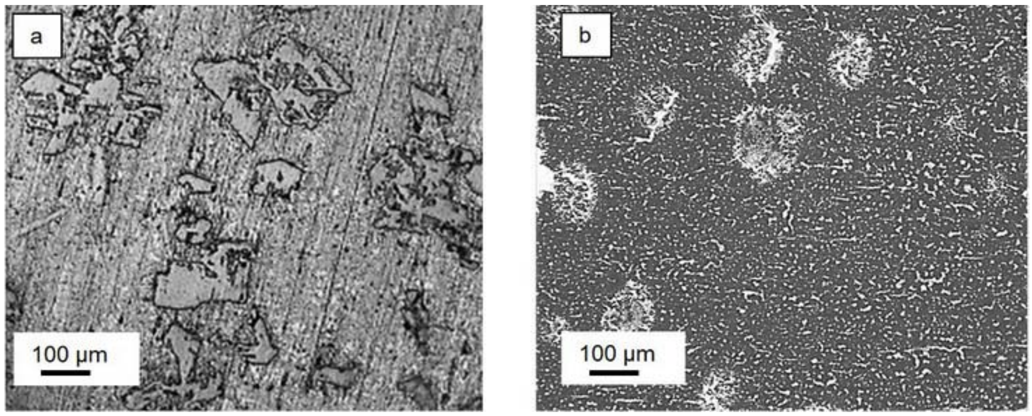


**FIG. 1:** An optical image of the hypereutectic silumin structure: a) in a cast state; b) after modification by an electron beam (20 J/cm$^2$, 150 μs, 0.3 s$^{-1}$, 5 pulses)

It was established that irradiation of silumin with a pulsed electron beam with the following parameters: accelerated electron energy 18 keV, electron beam energy density 15 J/cm$^2$, pulse repetition rate 0.3 s$^{-1}$, exposure time of the electron beam 150 μs, number of irradiation pulses 5, provides a more than 5 times increase in the hardness of specimens, compared with untreated specimens. It can be assumed that this effect is due to the formation of a submicrocrystalline eutectic containing partially dissolved silicon and intermetallic inclusions of the initial state. At a higher energy density of the electron beam, the hardness of the specimens decreases. This is due to the complete dissolution of the inclusions of silicon and intermetallic compounds and the participation in the hardening of only grains of submicrocrystalline eutectic.

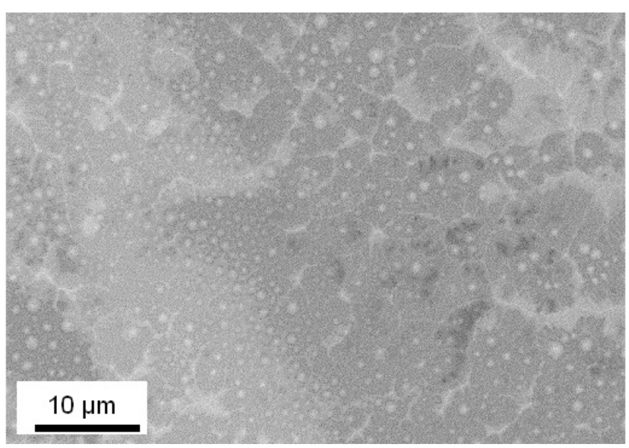


**FIG. 2:** SEM image of the hypereutectic silumin surface after modification by an electron beam (50 J/cm$^2$, 150 μs, 0.3 s$^{-1}$, 5 pulses)

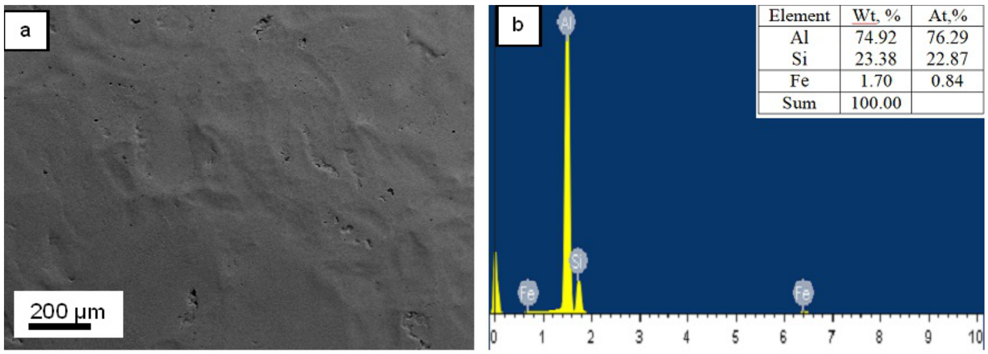


**FIG. 3:** SEM image (a) and energy spectra (b) of the silumin surface after modification by an electron beam (50 J/cm$^2$, 150 μs, 0.3 s$^{-1}$, 5 pulses)

During the experiment, specimens for tension were prepared from hypereutectic silumin according to the State Standard GOST 1497-84. As a result of tensile testing of proportional flat specimens, an increase in the strength of silumin from 76.6 MPa (cast state) to 97.2 MPa (after irradiation: 50 J/cm$^2$, 150 μs, 0.3 s$^{-1}$, 5 pulses) and a more than 2 times increase in tensile strain of irradiated specimens was revealed.

The main reason for the increase in the strength and plastic properties of silumin is a significant decrease in the number of micropores in the modified layer, dissolution of primary silicon crystals and intermetallic compounds, and formation, as a result of rapid cooling of the molten layer with a submicro-nanocrystalline multiphase structure. A decrease in the size of the structural elements of the hypereutectic silumin irradiated by a pulsed electron beam changes the nature of the fracture of the material: a brittle fracture is observed in the bulk (the crack extends along grain boundaries). The surface modified layer is destroyed with the formation of facets of a viscous fracture (Fig. 4). The size of the facets of destruction is 2.5–5 μm.

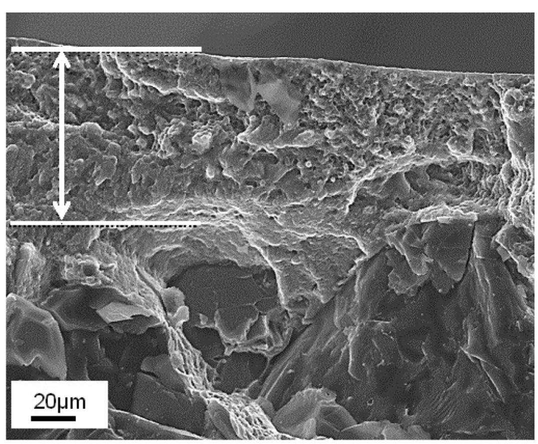


**FIG. 4:** SEM image of the surface structure fracture of a modified (50 J/cm$^2$, 150 μs, 0.3 s$^{-1}$, 5 pulses) hypereutectic silumin after tensile testing

## 4. CONCLUSIONS

It was revealed that the treatment of the hypereutectic silumin with an intense pulsed electron beam in the high-speed melting and crystallization of the surface layer is accompanied by the formation of a cellular crystallization structure with a quasi-uniform distribution of silicon atoms and impurity elements in the surface layer with a thickness of up to 100 μm. Modification of the silumin structure is accompanied by an increase in the microhardness of the surface layer by ≈ 5 times (15 J/cm$^2$, 0.3 s$^{-1}$, 5 pulses), a yield strength by a factor of two, with the ultimate strength (50 J/cm$^2$, 150 μs, 0.3 s$^{-1}$, 5 pulses).

## ACKNOWLEDGMENT

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