E. Petrikova, Y. Ivanov, M. Rygina, A. Prudnicov, A. Teresov and M. Vorobyov, "The Structure and Mechanical Characteristics of the Hypereutectic Silumin (Al–22–24 wt.% Si), Irradiated by a Pulsed Electron Beam," *2020* ***7th International Congress on Energy Fluxes and Radiation Effects (EFRE),*** 2020, pp. 460-463, doi: 10.1109/EFRE47760.2020.9241979.

Date of Conference: 14-26 Sept. 2020

Conference Location: Tomsk, Russia

Publisher: IEEE (Institute of Electrical and Electronics Engineers), New York

2020 7th International Congress on Energy Fluxes and Radiation Effects (EFRE 2020)

Tomsk, Russia
14-26 September 2020

Pages 1-674

IEEE Catalog Number: CFP20U59-POD
ISBN: 978-1-7281-2687-6

****** This is a print representation of what appears in the IEEE Digital Library. Some format issues inherent in the e-media version may also appear in this print version.***

IEEE Catalog Number:	CFP20U59-POD
ISBN (Print-On-Demand):	978-1-7281-2687-6
ISBN (Online):	978-1-7281-2686-9

Additional Copies of This Publication Are Available From:

Curran Associates, Inc
57 Morehouse Lane
Red Hook, NY 12571 USA
Phone: (845) 758-0400
Fax: (845) 758-2633
E-mail: curran@proceedings.com
Web: www.proceedings.com

7th International Congress on Energy Fluxes and Radiation Effects (EFRE) - 15th International Conference on Modification of Materials with Particle Beams and Plasma Flows - Tomsk - 2020

The Structure and Mechanical Characteristics of the Hypereutectic Silumin (Al–22–24 wt.% Si), Irradiated by a Pulsed Electron Beam

Elizaveta Petrikova
Institute of High Current Electronics SB RAS
2/3 Academichesky Ave., 634055, Tomsk, Russia
elizmarkova@yahoo.com

Yurii Ivanov
Institute of High Current Electronics SB RAS
2/3 Academichesky Ave., 634055, Tomsk, Russia
National Research Tomsk Polytechnic University,
30, Lenina Ave., 634050, Tomsk, Russia
yufi55@mail.ru

Maria Rygina
Institute of High Current Electronics SB RAS
2/3 Academichesky Ave., 634055, Tomsk, Russia
National Research Tomsk Polytechnic University
30 Lenina Ave., 634050, Tomsk, Russia
L-7755me@mail.ru

Alexander Prudnicov
Siberian state industrial University
42 Kirov Str., 654007
Novokuznetsk, Russia
a.prudnikov@mail.ru

Anton Teresov
Institute of High Current Electronics SB RAS
2/3 Academichesky Ave., 634055, Tomsk, Russia
tad514@yandex.ru

Maxim Vorobyov
Institute of High Current Electronics SB RAS
2/3 Academichesky Ave., 634055, Tomsk, Russia
vorobyovms@yandex.ru

Abstract—**Irradiation ("SOLO" setup, High-Current Electronics Institute SB RAS) of hypereutectic Al- (22–24) Si composition silumin samples with an intense pulsed electron beam was carried out. The formation of a multiphase submicron nanocrystalline structure is revealed. It was found that after modification, the hardness of silumin surface layer increases by more than 2 times. Tensile tests were carried out for flat proportional silumin samples in the initial and after irradiation states. An increase in the ductility of irradiated samples was demonstrated.**

Keywords—intense pulsed electron beam, aluminum, hypereutectic silumin, silicon, structure

I. Introduction

Silumin is a silicon and aluminum alloy. Silumin is an interstitial solution. The silicon content varies from 4 to 29 wt.%. At higher silicon values, the alloy loses its ductility. The ultimate solubility of silicon in aluminum is 1.65% at the eutectic temperature, and is 0.05% at the room temperature. In turn, aluminum in silicon dissolves only in an amount of 0.5% [1, 2]. According to the diagram, eutectic, hypoeutectic and hypereutectic solutions can be in equilibrium [3]. According to the percentage of silicon, silumins are divided into hypoeutectic (Si < 11%), eutectic (Si = 11–12.5%), hypereutectic (Si > 12.5%) [1].

Hypereutectic silumin is a promising aluminum alloy. Due to such properties as good fluidity, low weight, corrosion resistance can be used for the manufacture of machine parts and mechanisms. The structure of this alloy consists of eutectic and primary grains of silicon, as well as intermetallic compounds. These alloys belong to natural composites.

The work was supported by the Russian Science Foundation (project No. 20-79-10015).

Depending on the silicon content, the hardness of the hypereutectic silumin changes, the higher the silicon content, the higher the hardness [4]. Silicon is a fairly brittle material, with an increase in its concentration in the Al-Si alloy, processes of embrittlement of silumin occur. Primary silicon grains can reach sizes of 100 microns or more, what has a significant impact on the ability to operate the material. A significant effect on the size of the primary silicon grains is exerted by hydrogen, which gets from the air when casting the product into the mold. It is known that saturation of the melt with hydrogen complicates the further diffusion of silicon. At the moment, there are technologies to eliminate the fragility of silumin by alloying. The main disadvantage of alloying is that different modifiers are used to grind each phase. For example, beryllium binds iron [5], the addition of finely dispersed titanium or antimony to the melt reduces the size of primary silicon by 4 and 2 times, respectively [6]; to increase the dispersion of primary crystals of the α-phase of silumins, Al – B – Ti and Al – Zr ligatures are used. Aluminum-silicon eutectics are the most effectively modified by sodium-containing fluxes. Primary silicon crystals in hypereutectic silumins are mainly ground up by phosphorus-containing ligatures. In this case, the action time of sodium-containing fluxes usually does not exceed 0.5 h [7].

Another way to modify the structure of silumin is to change the method of casting products from this alloy. Thus, using centrifugal casting with water cooling, it was possible to obtain a microdimensional structure [8]. Silumins do not form chemical compounds, therefore, do not lend themselves to heat hardening treatment. The size of silumin grains and, accordingly, the strength characteristics of the material can be varied by changing the cooling rate [9].

978-1-7281-2686-9/20/$31.00 ©2020 IEEE

Of particular difficulty in casting products from silumins by traditional methods is the effect of heeredity, which manifests itself in maintaining the grain size when using finished castings as a charging material [10].

The method of modifying silumin by irradiating the surface of a part with an intense pulsed electron beam of micro- and submillisecond exposure duration allows one to achieve high heating and cooling rates. This method, as shown by studies performed on samples of hypoeutectic and eutectic silumins [3, 11–15], is one of the promising methods for modifying the surface layer of an alloy with a thickness of up to 1000 μm.

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

II. Experimental Setup

The material under study was hypereutectic silumin, the silicon concentration was (22–24) wt. %. Silumin of hypereutectic composition was prepared in a shaft-type laboratory electric resistance furnace with silicon carbide heaters in a painted stainless steel crucible. As a charge, we used commercially pure aluminum A7 (GOST 11069-2001) and silicon Kr0 (GOST 2169-69). The castings obtained were rectangular plates with dimensions of 55×120×20 mm. From the obtained ingot, rectangular specimens with dimensions of 15×15×5 mm were cut. Flat silumin specimens were prepared in the form of double-sided blades for tensile tests in accordance with GOST 1497-84 [16]. Some of the samples were irradiated with an intense pulsed electron beam ("SOLO" setup [17]) before testing. Irradiation mode: accelerated electron energy 18 keV, electron beam energy density 30 J / cm^2, pulse repetition rate 0.3 s^{-1}, electron beam exposure duration 150 μs, number of irradiation pulses 5. The irradiation mode was selected according to thermal calculations [18]. The samples were examined by optical (μVizo-MET-221), scanning (SEM-515 Philips), and transmission (JEM 2100 F) electron microscopy. Hardness tests were carried out on a PMT-3 installation. Tensile fracture tests were performed on an Instron 3369 setup.

III. Results And Discussion

A. Initial Structure of Hypereutectic Silumin

The initial structure of silumin specimens is represented by eutectic grains, primary silicon grains, and inclusions of intermetallic compounds based on silicon, aluminum, and iron. In fig. 1 shows an image of the initial structure of hypereutectic silumin. The primary silicon grains size reaches 100 microns. The study of the energy spectra of the surface of the original silumin, carried out by X-ray microanalysis, showed the presence of 23.0 wt. % silicon, the rest aluminum, traces of iron were also revealed (≤1 wt.%).

B. Structure of Modified Silumin Subjected to Pulsed Electron Beam Treatment

The surface layer of hypereutectic silumin was modified by irradiating the samples with an intense pulsed electron beam (30 J/cm2, 150 μs, 0.3 s^{-1}, 5 pulses). As shown in [18], the selected mode allows melting the silumin surface layer up to 60 μm thick. In this case, the silicon grains and intermetallics inclusions dissolution in the aluminum melt is recorded. Cellular structure is formed in this layer as a result of high-speed crystallization. The cells sizes vary within 250–400 nm (Fig. 2).

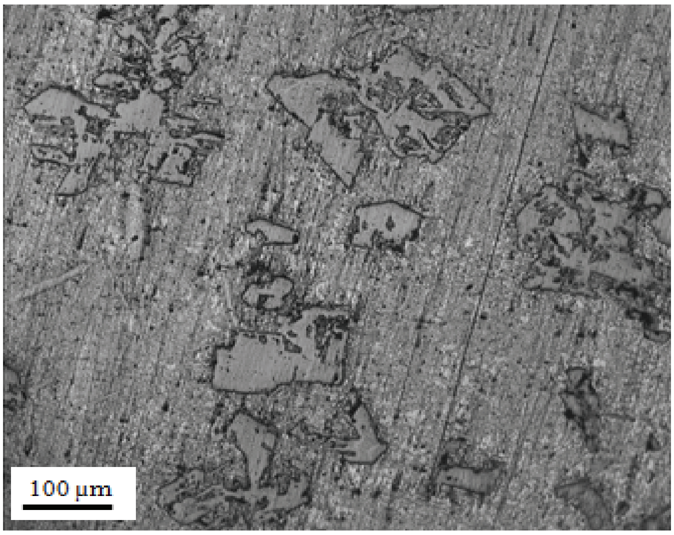


Fig. 1. Optical image of the initial structure of hypereutectic silumin.

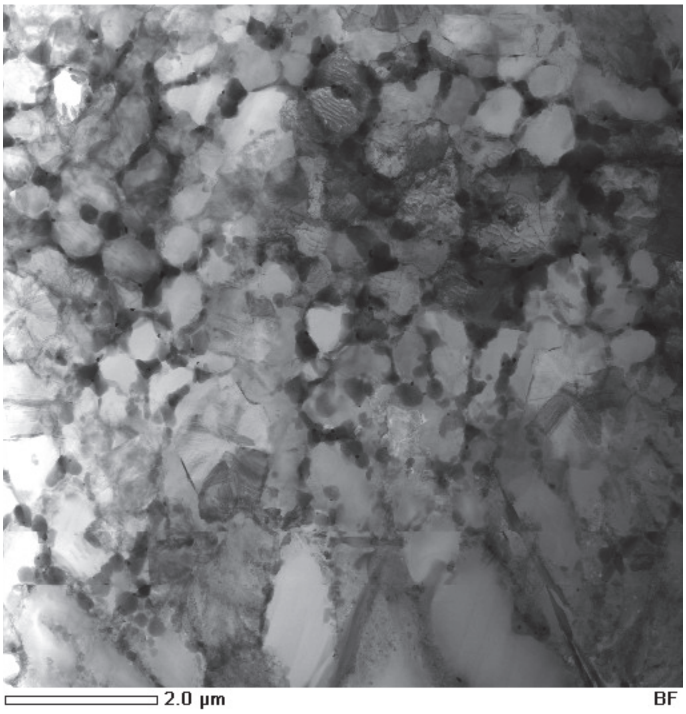


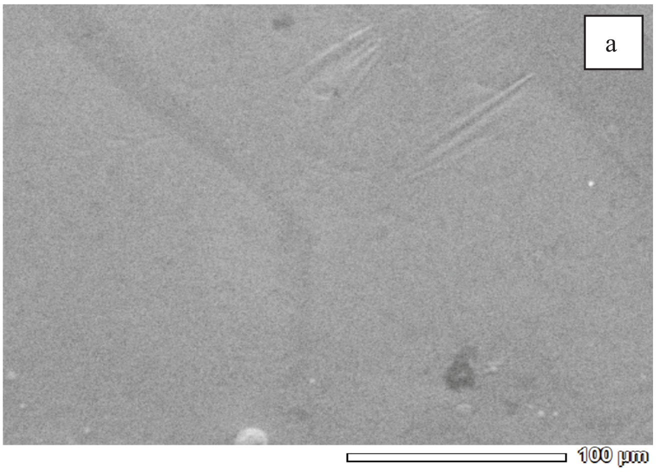
Fig. 2. Electron microscopic image of the hypereutectic silumin structure irradiated with an electron beam.

Nanosized particles of silicon and intermetallic compounds are located along the cell boundaries.

Fig. 3, a demonstrates the absence of primary grains, as well as gas pores that are formed in silumin at the casting stage.

The silicon content is 22.0 wt. %, iron – 1.0 wt.%, the rest is aluminum.

A high-speed crystallization characteristic of hypereutectic silumin, initiated by an irradiation with a pulsed electron beam, is the formation of globular silicon grains in the surface layer. In fig. 4 shows images of the silumin structure obtained in the characteristic X-ray radiation of silicon (fig. 4, a) and aluminum (fig. 4, b) atoms. Analyzing the results presented in this figure, it can be noted that the silicon grain size varies from 0.8 µm to 1.5 µm. In addition, silicon in the form of thin (up to 100 nm thick) interlayers is located, as noted above, along the high-speed crystallization of aluminum cells interfaces (Fig. 4, a). It should be noted that a change in the shape of silicon inclusions from predominantly lamellar in the initial state to globular, after irradiation with a pulsed electron beam, will facilitate the plasticization of silumin, reducing the likelihood of its brittle destruction due to cracking in silicon plates.



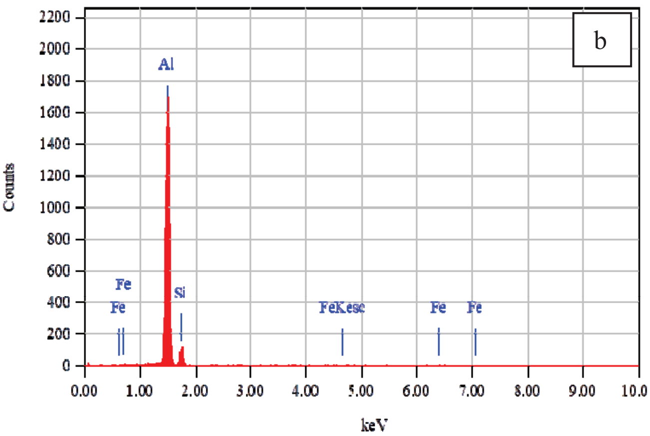


Fig. 3. SEM image (a) and energy spectra (b) of the silumin surface after modification with an electron beam (30 J/cm^2, 150 µs, 0.3 s^{-1}, 5 pulses).

C. *Mechanical Properties of Modified Silumin*

The microhardness of the hypereutectic silumin samples in the cast state was 1600 MPa; after irradiation the microhardness of silumin increased in 2.4 times and amounted to 3840 MPa. Tensile tests of hypereutectic silumin samples in the cast and electron-beam-irradiated states showed that the tensile strain of the cast silumin was 3.6%. After irradiation with a pulsed electron beam, the tensile strain increased by 1.5 and amounted to 5.4%.

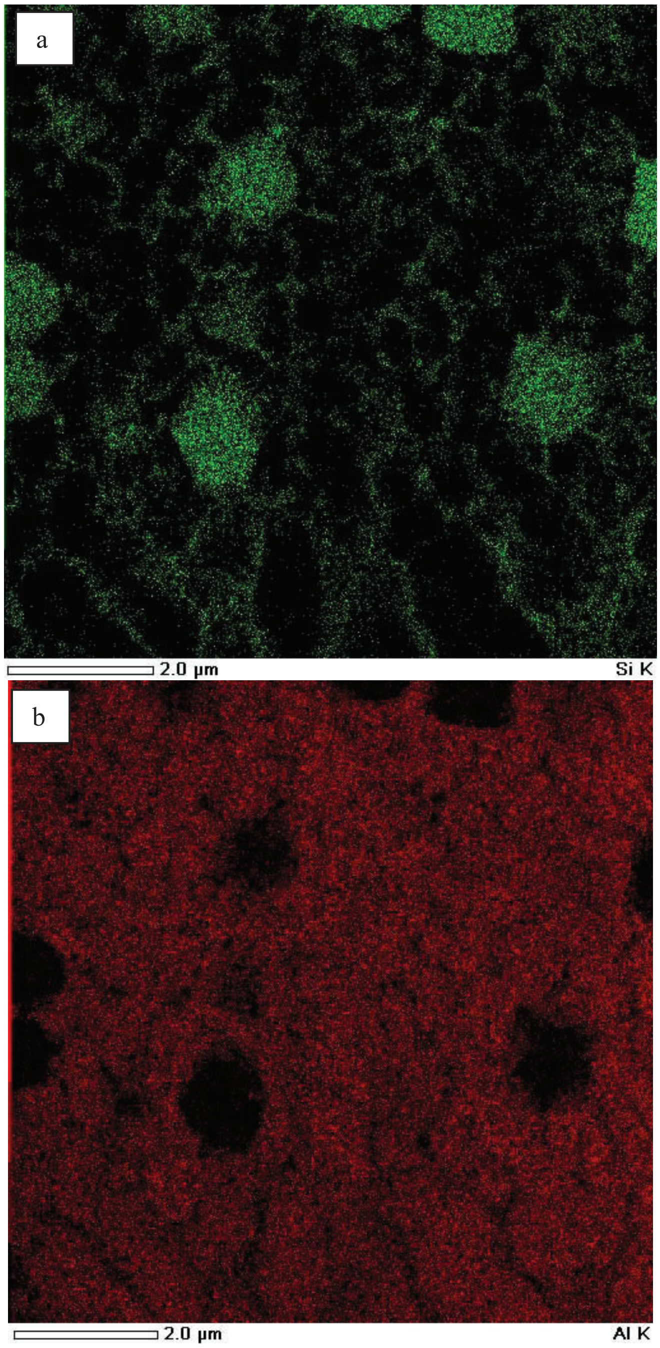


Fig. 4. Image of hypereutectic silumin structure irradiated with a pulsed electron beam (30 J/cm^2, 150 µs, 0.3 s^{-1}, 5 pulses), obtained in the characteristic X-ray radiation of silicon (a) and aluminum (b) atoms. Silumin layer at a distance of 20 microns from the irradiation surface.

IV. CONCLUSION

The irradiation of silumin with an intense pulsed electron beam in the mode of melting the surface layer (30 J/cm^2, 150 µs, 0.3 s^{-1}, 5 pulses) was carried out. It was found that high-speed crystallization leads to the formation of aluminum submicro-nanocrystalline cellular type structure. Interlayers enriched with silicon and iron atoms were revealed at the cells boundaries. It is shown that high-speed crystallization leads to the formation of globular silicon grains. It was found that irradiation of the silumin surface with a pulsed electron beam leads to an increase in hardness by more than two times and deformation in tension by a factor of 1.5.

Thus, the modification method proposed in this work, based on the use of an intense pulsed electron beam, can significantly increase the strength and plastic properties of hypereutectic silumin.

Acknowledgment

The work was supported by the Russian Science Foundation (project No. 20-79-10015).

References

[1] N. A. Belov, S. V. Savchenko and A. V. Khvan, *Phase composition and structure of silumin: Reference edition*. Moskow: "MISIS", 2007.

[2] M. Hansen and K. Anderko, *Binary alloy structures: Tran. from Eng.. T1*. Moskow: State. scientific and technical publishing house of literature on ferrous and non-ferrous metallurgy, 1962.

[3] A. P. Laskovnev, Yu. F. Ivanov, E. A. Petrikova *et al*., *Modification of the structures and properties of eutectic silumin by electron-ion-plasma treatment*. Minsk: Belarusian Navuka, 2013.

[4] Y. F. Ivanov, M. E. Gracheva, E. A. Petrikova, O. V. Krysina, A. D. Teresov, O. V. Ivanova and I. A. Ikonnikova, “Electron-Ion Plasma Modification of Al-based Alloys,” *AIP Conf. Proc*, vol. 1698, pp. 030012(1–8), October 2016.

[5] D. G. Pervakov, E. M. Baranov, D. V. Stroitelev and I. O. Romanov, “On the issue of the variety of approaches explaining the effects of modifying silumin,” *Scientific, technical and economic cooperation of the Asia-Pacific countries in the XXI century*, vol. 1, pp. 30–36, Febrary 2012.

[6] V. Yu. Stetsenko, A. I. Rivkin, A. P. Gutev and R. V. Konovalov, “Modification of silumins with fine-crystalline aluminum alloys,” *Bulletin of GSTU im. P.O. Sukhoi*, vol. 1, pp. 21–24, Febrary 2009.

[7] M. B. Altman and N. P. Stromskaya, *Improving the properties of standard casting aluminum alloys*. Moscow: Metallurgy, 1984.

[8] V. Yu. Stetsenko, K. N. Baranov and A. P. Gutev, “Cooling method of AK15M3 silumin castings with vertical centrifugal casting,” *Casting and metallurgy*, vol. 3(72), pp. 116–117, September 2013.

[9] E. A. Marukovich and V. Yu. Stetsenko, “Obtaining castings from hypereutectic force,” *Casting and metallurgy*, vol. 2(34), pp. 142–144, 2005.

[10] E. A. Marukovich and V. Yu. Stetsenko, “Improvement of structural heredity – reserve for increasing the properties of silumin,” *Casting and metallurgy*, vol. 3(57), pp. 16–18, Stptember 2010.

[11] D. Zaguliaev, S. Konovalova, Yu. Ivanov and V. Gromov, “Effect of electron-plasma alloying on structure and mechanical properties of Al-Si alloy,” *Applied Surface Science*, vol. 498, pp. 143767 (1–7), December 2019.

[12] Yu. F. Ivanov, V. E. Gromov, S. V. Konovalov, D. V. Zagulyaev, and A. P. Semin, “Formation of Structure and Properties of Silumin on Electron-Beam Processing,” *J. of Surface Invest.: X-ray, Synchrotron and Neutron Techn.*, vol. 13, pp. 1040–1044, November 2019.

[13] E. A. Petrikova, A. D. Teresov, M. E. Rygina (Gracheva) and Y. F. Ivanov, “Structure and mechanical characteristics of the hypereutectic silumin subjected to pulsed electron beam treatment,” *IOP Conf. Series: Materials Sci. and Engin.*, vol. 597, p. 012060(1–4), April 2019.

[14] Yu. F. Ivanov, D. V. Zagulyaev, S. A. Nevskii, V. E. Gromov, V. D. Sarychev, and A. P. Semin, “Microstructure and Properties of Hypoeutectic Silumin Treated by High-Current Pulsed Electron Beams,” *Progress in Physics of Metals*, vol. 20, pp. 451–490, March 2019.

[15] Yu. F. Ivanov, V. E. Gromov, S. V. Konovalov, D. V. Zagulyaev, and E. A. Petrikova, “Structural-Phase State and the Properties of Silumin after Electron-Beam Surface Treatment,” *Russian Metallurgy (Metally)*, vol. 2019, pp. 398–402, April 2020.

[16] GOST 1497-84. Metals. Tensile test methods: Moskow: Standartinform, 2005.

[17] N. N. Koval and Yu. F. Ivanov, “Nanostructuring of the surface of cermet and ceramic materials during pulsed electron-beam processing,” *Russian Physics Journal*, vol. 51, pp. 60–70, May 2008.

[18] Yu. F. Ivanov, E. A. Petrikova, O. V. Ivanova, I. A. Ikonnikova and A. V. Tkachenko, “Numerical simulation of the temperature field of silumin irradiated with an intense electron beam,” *Russian Physics Journal*, vol. 58, pp. 46–51, April 2015.