Surface modification of hypereutectic silumin subjected to a millisecond modulated electron beam treatment

K T Ashurova, M S Vorobyov, E A Petrikova, Yu F Ivanov, P V Moskvin and M E Rygina

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia

E-mail: 11k.ashurovak@gmail.com

Abstract. In this work, using a unique feature of the "SOLO" electron source with a grid plasma cathode based on a low-pressure arc discharge, which consists in the possibility of controlled operation of the beam power during a pulse of submillisecond duration, and, accordingly, the rate of energy input into the sample surface, we investigated the modes irradiation of samples of hypereutectic silumin. The irradiation modes had the same energy density during the first 200 μs of the pulse, equal to 20 J/cm² and differed in different durations of further maintaining the surface temperature at 600°C for a time of up to 1 ms. The results of tribological tests and methods of diffraction microscopy of the investigated defect structure, the elemental and phase composition, the morphology of the strengthening phases of the modified layer of the hypereutectic silumin samples are presented.

1. Introduction

Today, one of the most promising materials in the field of aircraft and mechanical engineering is hypereutectic silumin, with a silicon content of more than 13% [1]. It is due to this feature that hypereutectic silumin has the high hardness and heat resistance. The main problem of using this material is its fragility due to the release of silicon in the form of coarse inclusions. The presence of large primary crystals of silicon and intermetallic phases increases the likelihood of cracking and reduces the mechanical properties of the material [2]. That is why, for the practical use of hypereutectic silumin as a structural material, it is necessary to solve a number of problems associated with their unsatisfactory physical and mechanical properties. One of the most effective methods of increasing the strength characteristics of the entire material as a whole is the treatment of its surface with an intense electron beam, which makes it possible to refine the structure of the surface layer [3].

2. Experimental setup

In this work, hypereutectic silumin with silicon content (18-22) wt.%, as one of the most frequently used and promising materials, was used as a material for the study [4]. Irradiation of the sample surface was carried out using electron beam source «SOLO» generating an electron beam with a diameter of up to 5 cm with an electron energy of up to 25 keV, an adjustable pulse duration (20-1000) μs and an energy density of up to 100 J/cm², which makes it possible to change these parameters in a controlled manner smoothly and independently of each other [5]. In order to show these properties
of beam sources with plasma cathode we have conducted experiments [6] and obtained theoretical assessments that confirmed the possibility of generating pulsed beams of millisecond duration with controlled power variation during the pulse. With the help of these estimations we have created a source of power supply for a plasma cathode [7] and experimentally demonstrated that it is possible to provide proportional dynamic variation of pulsed electron beam current during the pulse by dynamic variation of the discharge current and, therefore the concentration of emissive plasma [8].

For surface treatment, the following modes were selected: quasi-rectangular beam current pulse with an amplitude of 80 A and a duration of 200 μs at an accelerating voltage of 15 keV with a beam energy density of 20 J/cm² (mode 1 in table 1); the same rectangular pulse with the further keeping the temperature at the level of 600°C for 400 μs (mode 2 in table 1); rectangular pulse with the temperature holding at 600°C for 800 μs (mode 3 in table 1). Figure 1 (a) shows oscillograms of the discharge current $I_d$, beam current $I_g$, and accelerating voltage $U$ for irradiation mode No 1. However, from these characteristic oscillograms, one can see how energy was deposited in modes 2 and 3, which was achieved by shortening the pulse duration at the same start. In the figure 1 (b) it is also can be seen how the surface temperature of sample No 1 changed, but from it can be understood how the surface temperature of samples No 2 and No 3 changed.

![Figure 1](image-url). Oscillogram of the discharge current ($I_d$), current in the accelerating gap ($I_g$), accelerating voltage ($U$) (a); temperature change during pulse (b).

| No | Energy density (J/cm²) | Main pulse duration (μs) | Duration of temperature holding (μs) | Holding temperature (°C) |
|----|------------------------|--------------------------|-------------------------------------|--------------------------|
| 1  | 20                     | 200                      | –                                   | –                        |
| 2  | 20                     | 200                      | 400                                 | 600                      |
| 3  | 20                     | 200                      | 800                                 | 600                      |

3. Experimental results
As a result of measuring the hardness of the surface layer and tribological tests, it was found that irradiation of hypereutectic silumin at 20 J/cm² for 200 μs with an additional holding of the temperature near the melting point for 800 μs (sample No 3) in comparison with other samples leads to a maximum increase wear resistance and a decrease in the rate of wear of the surface of the material, namely, microhardness - by 2.2 times, the rate of wear - by 3.7 times in comparison with an unirradiated sample. Therefore, for further studies, a sample of hypereutectic silumin irradiated in mode No 3 was selected.
The structure of the modified layer was analyzed by transmission electron microscopy, the results of which are shown in figure 2. It has been established that as a result of irradiation, large silicon inclusions are reduced in size, and a structure characteristic of the eutectic of aluminum and silicon alloys is formed in the surface layer, which is expressed in the alternation of silicon and aluminum interlayers (figure 2 (b)).

![Figure 2](image2.png)

**Figure 2.** The structure of the silumin sample before treatment (a) and after (b)

It was established by X-ray microanalysis that a structure of high-speed cellular crystallization is formed in the modified layer, and the volume of crystallization cells is formed by a solid solution based on aluminum (figure 3). The cells are separated by interlayers with a lamellar structure. These interlayers are predominantly enriched in silicon atoms. Along with silicon and aluminum atoms, iron, copper and oxygen atoms were found in the material, the relative total content of which is (1-2) wt. %.

![Figure 3](image3.png)

**Figure 3.** Silumin structure after irradiation with a pulsed electron beam (20 J/cm², 200 μs, the time the temperature was held at 600°C for 800 μs); the images were obtained in characteristic X-ray radiation of aluminum (a) and silicon atoms (b).

Analysis of the results presented in figure 3 shows that high-speed crystallization of the molten surface layer of silumin, upon irradiation of the silumin with a pulsed electron beam, is accompanied by the formation of a submicro-nanocrystalline structure in the surface layer up to 80 μm.
4. Conclusion
Based on the results of studies of the structural-phase state of silumin, performed by transmission electron diffraction microscopy, it can be concluded that the revealed increase in the wear resistance of the samples is due to the formation of a cellular structure and crushing of large inclusions of silicon and intermetallic compounds. For an unambiguous answer, it is required to increase the temperature retention time, which may require more experiments.

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

References
[1] Rygina M E, Ivanov Yu F, Laskovnev A P, Teresov A D, Cherenda N N, Uglov V V and Petrikova E A 2018 J. Phys.: Conf. Ser. 1115 032054
[2] Gromov V E, Yurev A B, Morozov K V and Ivanov Yu F 2016 The microstructure of quenched Rails (Great Britain: Cambridge international science publishing)
[3] Gromov V E, Ivanov Yu F, Vorobiev S V and Konovalov S V 2015 Fatigue of steels modified by high intensity electron beams (Great Britain: Cambridge International Science Publishing)
[4] Devyatkov V N, Ivanov Yu F and Krysina O V Vacuum 143 464–472
[5] Vorobyov M S, Moskvin P V, Shin V I, Koval N N, Ashurova K T, Doroshkevich S Yu, Devyatkova V N, Torba M S and Levanisov V A 2021 Zh. Tekh. Fiz. 47 38–41
[6] Vorobyov M S and Kovalsky S S 2019 J. Phys.: Conf. Ser. 1393 012035
[7] Vorobyov M S, Koval N N, Moskvin P V, Teresov A D, Doroshkevich S Yu, Yakovlev V V and Shin V I 2019 J. Phys.: Conf. Ser. 1393 012064
[8] Koval’ N N, Oks E M, Protasov Yu S and Semashko N N 2009 Emission Electronics (Moscow: MGTU im. N. E. Baumana)