Structure and mechanical characteristics of the hypereutectic silumin subjected to pulsed electron beam treatment

E A Petrikova[1], A D Teresov[1], M E Rygina[1,2] and Yu F Ivanov[1,2]

[1]Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, 2/3, Akademicheskiy ave., Tomsk, 634055, Russia
[2]Tomsk Polytechnic University, 30, Lenina ave., Tomsk, 634050, Russia

E-mail: elizmarkova@yahoo.com

Abstract Silumin, aluminum with silicon alloy, is a promising material used for the manufacture of medium-loaded machine parts and mechanisms. High brittleness is one of the main drawbacks of hypereutectic silumin. Modification of a hypereutectic silumin (18–20 wt.% Si) was carried out by irradiating the samples with an intense pulsed electron beam. It was established that irradiation of cast hypoeutectic silumin by an electron beam leads to a significant reduction in the number of micropores, forming a high-speed cellular crystallization structure with a cell size of (0.4-0.6) μm. An irradiation mode allowing to increase the silumin surface layer hardness by more than 4 times, wear resistance - by 1.2 times, to increase ductility by 1.2 times in relation to the initial material was detected (35 J / cm^2; 200 μs, 20 imp. 0.3 s^{-1}).

1. Introduction

Silumin is aluminum based alloys with different silicon content. These alloys belong to the class of eutectic materials. Silumins are widely used in such industries as aircraft, enginery and shipbuilding for the manufacture of medium-loaded parts - pistons, bearings, housings, etc. An increased interest has been caused by the use of hypereutectic silumins in recent decades. Such materials are characterized by high hardness and wear resistance due to the high content of silicon. The main disadvantages of hypereutectic silumins include the high porosity of products, that origin is associated with a high content of hydrogen in ligatures, the presence in the structure of primary silicon crystallites with a transverse size of hundreds of micrometers [1-3]. These and some other features of the structural-phase state of the hypereutectic silumins lead to their increased brittleness, which significantly reduces the field of industrial application.

Modification of the material at the stage of formation or the use of various methods of casting, for example, with characteristics of centrifugal lithium is the main way to eliminate the mentioned disadvantages of hypereutectic silumins are used in industry. Both approaches have their drawbacks, so with centrifugal casting there is a limit on the weight (not more than 500 g) and the shape (ring) of the work piece [4].

Methods based on the use of concentrated energy flows (laser processing, plasma flow processing, powerful ionic and low-energy electron beams, the method of electric flashing in a magnetic field and some others) are used for the purpose of modifying the structure and properties of metals and alloys, including silumin in recent years [5-7]. Ultra-high speeds (up to 109 K / s) of heating to melting temperatures and subsequent cooling of a relatively thin surface layer of the material (10^{-7}-10^{-6} m), forming in it extreme temperature gradients (up to 107 ... 108 K / m) providing cooling the surface layer

due to the heat sink into the main volume of the material at a speed of 104 ... 109 K / s, create conditions for the formation in the surface layer from one to hundreds of micrometers thickness of a nano- and submicrocrystalline structure. In total, this contributes to an increase in corrosion resistance, wear resistance and microhardness, fatigue life of the irradiated material, which is unattainable with traditional surface treatment methods [7–9].

The aim of this work is to analyze the results obtained in the study of the structure and properties of hypoeutectic silumin subjected to modification by an intense pulsed electron beam.

2. Materials and methods

The material under study was hypereutectic silumin with a silicon content of 18 to 20 wt.%. Modification of silumin was carried out in vacuum at a residual pressure of the working gas (argon) of 0.02 Pa on the SOLO setup [10]. Irradiation mode: the accelerated electron energy is 18 keV, the electron beam energy density is (15-35) J / cm^2, the pulse repetition rate is 0.3 s^{-1}, the duration of the electron beam exposure is 200 μs, the number of impact pulses is 20. The detected irradiation regimes, according to thermal calculations [11, 12], corresponded to the melting of the surface layer of silumin up to 100 μm thick. Part of the samples before irradiation was made in the form of blades for tensile testing in accordance with GOST 1497-84 [13]. The working area of the blades was irradiated from both sides by an electron beam. Tests of the initial and irradiated samples before destruction were carried out on an Instron3369 setup at a tensile rate of 0.2 mm / s. The structure of the samples after irradiation and the structure of the damage surface was investigated by scanning electron microscopy (SEM-515 Philips). Hardness tests were carried out on the device PMT-3.

3. Results

The structure of the samples of the eutectic silumin in the cast state (the state before electron beam irradiation) consists of eutectic grains, grains of primary silicon and intermetallic compounds [14]. Samples of silumin in the initial state contain a large number of pores that sizes vary from units to tens of micrometers. The initial sample hardness was 890 MPa, the wear parameter (inverse of wear resistance) was $5.86 \cdot 10^{-4}$ mm^3 / N·m, and the friction coefficient was 0.44.

The irradiation of hypereutectic silumin samples with an intense pulsed electron beam leads to the formation of a high-speed cellular crystallization structure (Fig. 1a). The dimensions of solid solution based on aluminum cells vary within (0.4–0.6) μm (Figure 1, b).

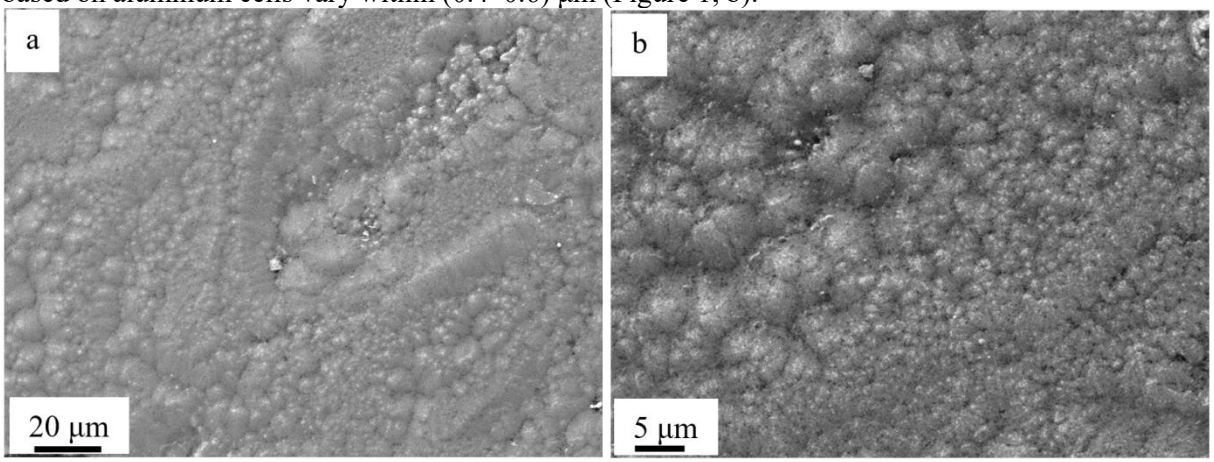

Figure 1. Structureofthesurfaceofthehypereutecticsiluminirradiatedwithanintensepulsedelectronbeam (35 J / cm^2; 200 μs, 20 pulses 0.3 s^{-1}).

The microhardness of the irradiated samples was 4580 MPa; wear parameter $4.96 \cdot 10^{-4}$ mm^2 / N·m, friction coefficient 0.43. Thus, the completed tests showed that the irradiation of silumin with an electron beam led to a significant increase in the microhardness and wear resistance of the surface layer of the material.

The deformation curves of silumin subjected to an intense pulsed electron beam are shown in Figure 2. It is clearly seen that electron-beam treatment of silumin leads to an increase in the plasticity of the material with an increase in the energy density of the electron beam. Comparing the results obtained in tensile tests of silumin in the initial state and after irradiation, it is possible to note an increase in the plasticity of the irradiated samples by 1.2 times. The ultimate strength of the initial and electron beam irradiated (35 J / cm^2; 200 μs, 20 imp. 0.3 s^{-1}) samples are the same.

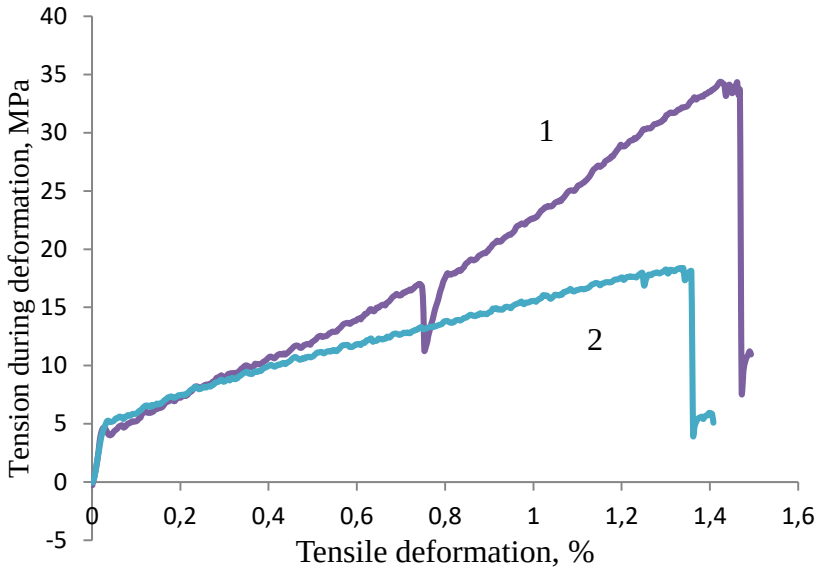

Figure 2. Deformation curves of the hypereutectic silumin subjected to electron beam irradiation (200 μs, 20 imp. 0.3 s^{-1}): curve 1 - 35 J / cm^2; curve 2 is 15 J / cm^2.

It should be assumed that the increase in plasticity of silumin, irradiated by an intense pulsed electron beam, is due to the transformation of its structure. Figures 3 and 4 show electron microscopic images of the destruction surface of the eutectic silumin in the initial state (Figure 3) and after irradiation with an intense pulsed electron beam (Figure 4).

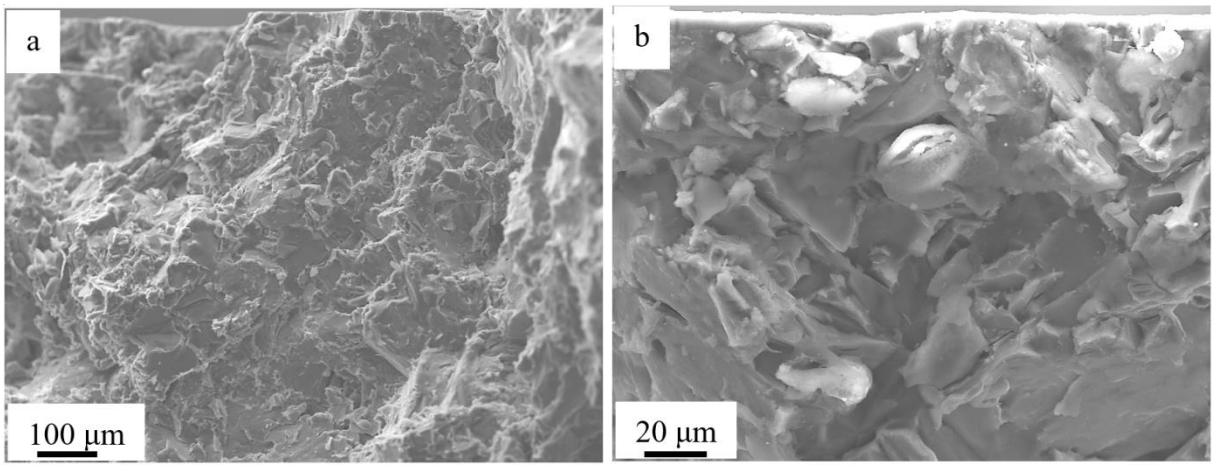

Figure 3. The structure of the surface destruction of the hypereutectic silumin in the initial state.

It is clearly seen that the fracture of silumin in the cast state is predominantly brittle (Figure 3, b). The irradiation of the silumin surface with an intense pulsed electron beam and the subsequent destruction as a result of the tensile test is accompanied by the formation of viscous fracture cells in the surface layer up to 100 μm thick (Figure 4, a). Cell sizes range is from 0.5 μm to 2 μm. It is obvious that

the formation of such a structure is a consequence of the high-speed crystallization of the surface layer of silumin, which takes place during irradiation with an intense pulsed electron beam.

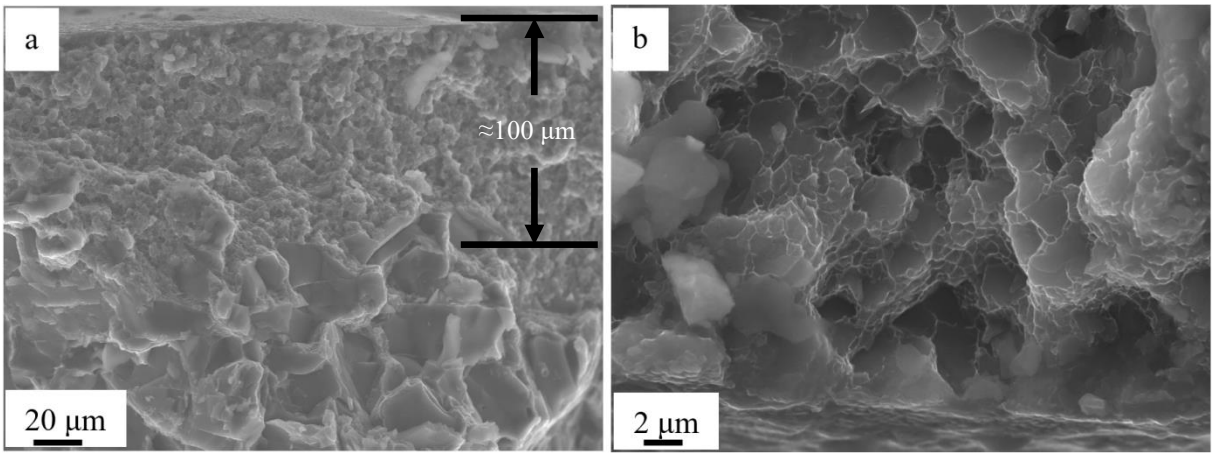

Figure 4. The structure of the destruction surface of the hypereutectic silumin subjected to an intense pulsed electron beam (35 J / cm^2; 200 μs, 20 pulses 0.3 s^{-1}).

4. Conclusion

It was established that the irradiation of the surface of cast hypereutectic silumin samples (silicon content (18–20) wt.%) by an intense pulsed electron beam is accompanied by a significant decrease in the number of micropores, as well as the formation of a high-speed cellular crystallization structure with a cell size (0.4–0.6) μm as a result of the conducted research. An irradiation mode of silumin with an intense pulsed electron beam (35 J / cm^2; 200 μs, 20 imp. 0.3 s^{-1}) was detected, which makes it possible to increase the hardness of the surface layer of the irradiated samples by more than 4 times, the wear resistance is 1.2 times relative to the initial material. The increase in these characteristics is associated with the grinding of the microstructure. The tensile tests of silumin in the initial state and state after irradiation with an electron beam (35 J / cm^2; 200 μs, 20 imp. 0.3 s^{-1}) revealed an increase in the plasticity of the irradiated samples by 1.2 times. The ultimate strength of the initial and electron-irradiated samples did not change.

Acknowledgments

This work was supported by the RFBR grant (project No. 19-52-04009 Bel_mol_a).

References

[1] Wladysiak R, Kozun A, Debowska, K andPacyniak T 2017 *Arch. foundry eng.*-**17 (2)** 137-44
[2] Yi LF, Yoshida N, Yamamoto T, Onda T and Chen Z.-Ch.2019 *J. mater. sci*. **54 (13)** 9933-44
[3] Nehrkorn S, Handel M, Dietrich D, Podlesak H, Nickel D, Wielage B and Lampke T2014 *Sur. Coat. Tech.* **242** 118–24
[4] Stetsenko V, Baranov K and Gutev A 2013 *Cast. and metals* **3 (72)** 116-7
[5] Mikheev R and Chernyshova T. 2009 *Metals* ***(*****6)** 53-9
[6] Wong T and Liang G 1997 *J. Mater. Proc.Tech.* **63** 930-4
[7] Laskovnev A, Ivanov Y, Petrikova E, Koval N, Uglov V, Cherenda N, Bibik N and Astashincky V 2013 *Modification of the structure and properties of eutectic silumin electron-plasma processing* (Minsk: Belorussian navuka)
[8] Ivanov Y, Gromov V, Konovalov S and Aksenova K 2016 *Fatigue of silumin modified by electron beam processing* (Novokuznetsk:Poligraphist)
[9] Rotshtein V, Ivanov Yu and Markov A 2006 Surface treatment of materials with low-energy, high-current electron beams *Materials surface processing by directed energy techniques* ed Y

Pauleau: Elsevier chapter 6 pp 205-40
[10] Koval N and Ivanov Y 2008 *Rus. Phys. J.* **5** (51) 505-16
[11] Ivanov Yu, Petrikova E, Ivanova O, Ikonnikova I, Teresov A, Shugurov V and Krysina O 2015*Rus. Physics J.* **58** (3) 373-9.
[12] Ivanov Yu, Petrikova E, Ivanova O, Ikonnikova I and Tkachenko A 2015 *Rus. Phys. J.* **58** (4) 478-84
[13] GOST 1497-84 2005 Metals. Tensile test methods (Moskow:Standardinform)
[14] Rygina M, Ivanov Y, Laskovnev A, Teresov A, Cherenda N, Uglov V, Petrikova E and Astashinskaya M 2016 IOP Conf. Ser.: Mater. Sci. and Eng. **124** 1-5