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Structure-phase states of silumin surface layer after electron beam and high cycle fatigue

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Abstract. Modification of eutectic silumin surface has been implemented by high-intensity pulsed electron beam. The irradiation mode has been revealed; it allows increasing silumin fatigue life in more than 3.5 times. It has been established that the main reason of this fact is the formation of a multiphase submicro- and nanosized structure. It has been elicited that the most danger stress concentrators are large silicon plates situated on the surface and near-surface layers.

1. Introduction

Currently, in various branches of industry aluminum alloys are becoming increasingly popular. The most common of them is an aluminum alloy with silicon – silumin. This is due to its relatively low cost and low specific gravity. However, the relatively low strength properties of silumin narrow significantly its scope of application. Silumins are not strengthened by heat treatment, because of the small differences in the solubility of silicon at high and low temperatures. Therefore, the most important method of improving their mechanical properties is the modification [1]. The most effective method of the specified modification is the treatment of material surface by high-intensity pulsed electron beam. It allows modifying the structure of the surface layer with a thickness of tens of micrometers, turning it into a multi-modal structural-phase state and almost without changing the structural-phase state of the bulk of the alloy [2]. As shown in works [3-7], the formation of such surface structural-phase states contributes to the improvement of steel fatigue life of different structural classes in 2-3.5 times.

The aim of this work is to study the structural-phase states, which are formed in the surface layer of silumin, subjected to electron beam irradiation and high-cycle fatigue testings up to the fracture.

2. Materials and research methods

Silumin of a grade AK12 was used as a material for study. Fatigue tests, as in [3-7], were carried out on a special installation according to the scheme of an asymmetrical cantilever bending. The samples had the shape of a parallelepiped with dimensions 8x14x145mm. Simulation of crack was carried out by a cut in the form of a semicircle of radius 10 mm. Test temperature is of 300 K, the frequency of sample loading by bending – 15 Hz with a load of 10 MPa. Irradiation of the sample surface, prepared for fatigue testing was carried out at the device "SOLO" [2] with the following parameters: electron energy of 16 keV; the pulse frequency 0.3 s^{-1}; duration of the electron beam pulse of 50 μs and 150 μs; the energy density of the electron beam (10...25) J/cm^2; the number of the exposure pulses – 1, 3, 5. The front surface of the samples was irradiated, that is, the sample surface located over the incision simulating the crack. Each irradiation mode tested at least 5 samples. Examination of electron-beam exposure and fracture surface was carried out by methods of optical and scanning electron diffraction microscopy.

3. Results and their discussions

The structure of silumin before electron beam irradiation (the structure of the original state) is characterized by the presence of relatively large (from tenths to tens of micrometer) inclusions of silicon predominantly of a lamellar morphology (Fig. 1).

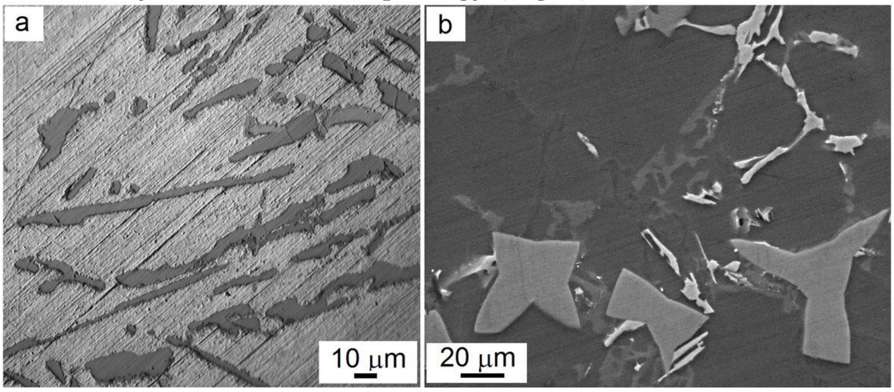

Fig. 1. Structure of silumin of the original state (before intense electron beam irradiation); a – optical microscopy; b – scanning electron microscopy.

In the fatigue tests of silumin samples a non-monotonic dependence of the number of cycles up to fracture on the irradiation mode by high-intensity pulsed electron beam has been received (Table 1). In the initial state silumin samples withstood N=1.3 10^5 the number of cycles up to the fracture. The greatest increase in fatigue life (~3.5 times) has been provided by the irradiation mode No. 4.

Table 1. Dependence of a circle number up to the fracture on the irradiation mode by electron beam.

Number of the mode	Beam energy density, E_S, J/cm^2	Exposure time, τ, μs	Number of pulses, n, pulse	Total power density, W*n, 10^6, $Wt*pulse/cm^2$	<N>, 10^5, cycles
1	20	150	1	0.13	1.32
2	15	150	3	0.30	1.80
3	25	150	3	0.50	2.70
4	20	150	5	0.67	5.17

5	10	50	5	1.00	2.09

It is evident that the fatigue life of silumin is determined primarily by the structure of the surface layer, modified by electron-beam processing. For structural studies of the irradiation surface of silumin the samples have been selected; they have showed minimal (for mode No. 2) and maximum (for mode No. 4) fatigue life.

The irradiation of silumin surface with pulsed electron beam depending on the energy density of the electron beam is accompanied either by melting the surface of the sample (Fig. 2, a, b), or the melting of the surface layer of the material of a certain thickness (from one to tens of micrometers) (Fig. 2, c, d). In the first case, the fatigue life in some cases has been below the fatigue life of the initial samples, and in the second one it has exceeded the fatigue life of the initial material in more than 3.5 times.

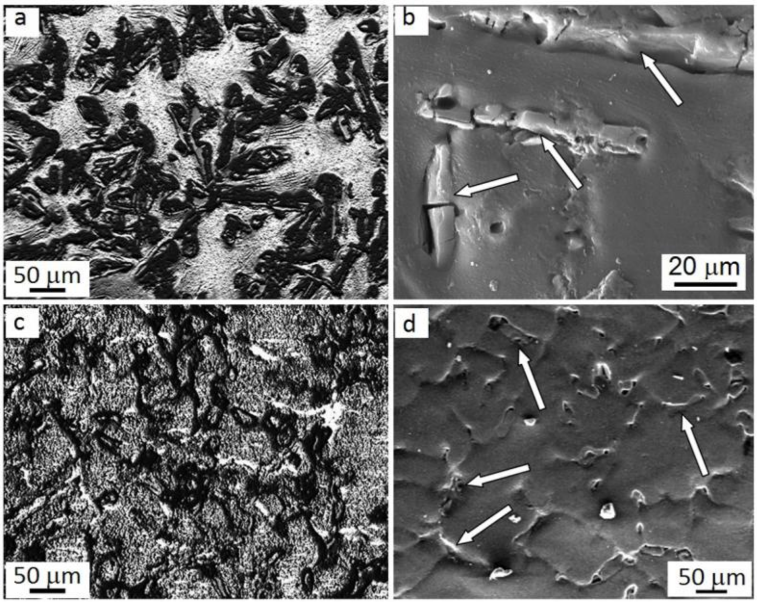

Fig. 2. Surface structure of silumin irradiated by electron beam in modes No. 2 (a, b) and No. 4 (c, d); a, c – optical microscopy; b, d – scanning electron microscopy; silicon particles are arrowed on (b, d).

The irradiation of silumin surface for mode No. 2 leads to the partial melting of the excess silicon inclusions (Fig. 2, a). In the surface layer numerous micropores along the boundary between the plate/matrix and microcracks are formed; they are located in the silicon plates, which weaken the material. On the image of fatigue fracture surface of the silumin sample (Fig. 3) it can be clearly seen that the fatigue crack is formed on the sample surface (Fig. 3, a). The reasons for the formation of fatigue cracks are coarse inclusions of silicon (Fig. 3, b), which are stress concentrators. As a result, the fatigue tests lead to the fracture of plates and the formation of long microcracks.

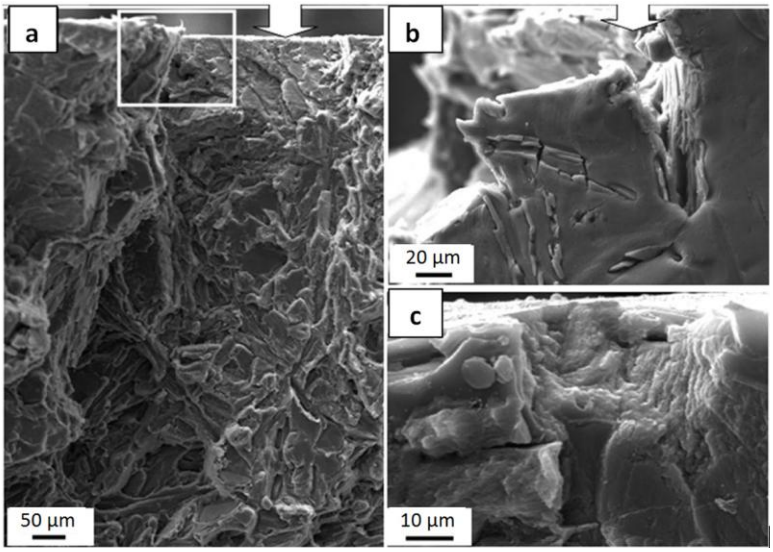

Fig. 3. Electron microscope image of the fracture surface structure (a, b) and irradiation surface (b) of silumin, processed by electron beam according to mode № 2. On (a) the frame singles out a fatigue crack formation range; the pointers indicate: on (a) – irradiation surface, on (b) – place of origin of fatigue crack.

During silumin irradiation with high-intensity electron beam in mode No. 4 the structure of the surface layer by morphological characteristic differs significantly from the structure of the original sample (Fig. 1) and the sample irradiated in the mode of the surface melting (Fig. 2, a, b). On the irradiation surface the homogeneous structure of a grain type is formed (Fig.2 (c, d), and the thickness of the molten layer varies in the range up to 20 µm (Fig. 4, d).

Fatigue fracture surface analysis of the sample irradiated by the electron beam in mode No. 4, showed that the thickness of the melted layer varies in the range up to 20 µm (Fig. 4, a). Subsequent to the melting high-speed crystallization leads to the formation of multimodal structures represented at the macro level by the aluminium based grains, sizes of which varies within 30...50 µm with located on the boundary silicon particles, whose dimensions do not exceed 10 µm (Fig. 2, c, d). Two-phase (silicon and solid solution on the basis of aluminum) crystallization cells detected on the fatigue fracture surface form meso-level of modified layer. Crystallization cell sizes vary from 100 nm to 250 nm (Fig. 4, b). This reflects the submicrocrystalline structure of the near-surface layer. It is important that the stress concentrators, which can be a source of fracture of silumin samples at this mode of irradiation, on the edge of a fracture are not revealed. Apparently, the concentrators, which caused the fracture of the sample, are situated below the surface, most likely at the interface of the liquid and solid phases. It can be assumed that one of the possible reasons for the decline in the number of cycles up to the fracture to the initial state after irradiation of the silumin samples according to mode No. 5 can be a powerful residual thermal stresses, emerging in the modified surface layer, as in [8].

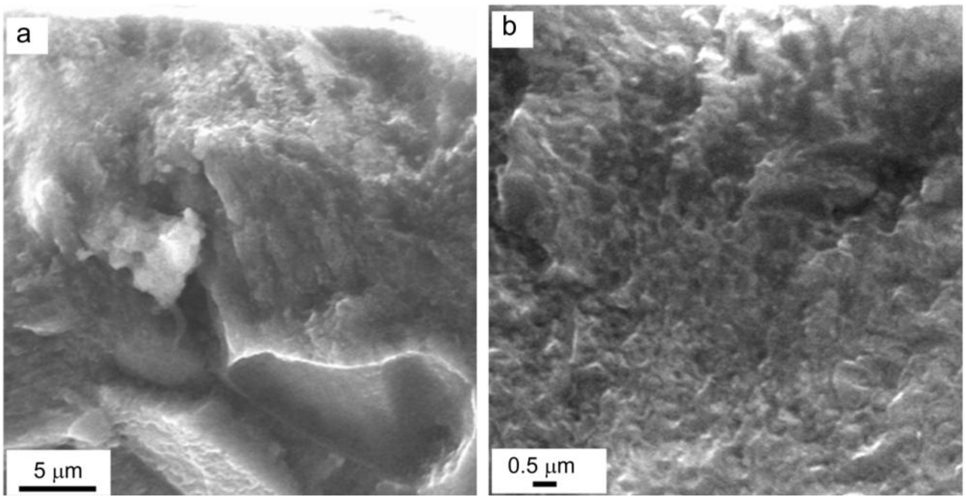

Fig. 4. Electron microscope image of fatigue fracture surface of silumin treated in mode of irradiation by high intensity pulsed electron beam No. 4.

The formation of multi-level structural-phase state determines the development of the damping properties in the surface layer of the modified silumin with respect to the main material by mechanical and thermal external influences. This prevents the premature birth and spreading of fragile microcracks from the surface into the bulk of the material. These cracks can lead to the formation of main cracks and to the fracture of the basic material [9]. Thus, the formation of a submicro-and nanosized multiphase structure at the irradiation of silumin according to mode No. 4 is also the defining reason assisting a multiple increase of its fatigue life.

4. Conclusion

Multicycle fatigue tests up to the fracture of silumin samples subjected to the electron-beam processing have been carried out. The irradiation mode, that promotes the multiple increase (in more than 3.5 times) of fatigue life of silumin, has been identified.

The researches of an irradiation surface structure and the surface of fatigue failure of silumin in an initial state and after modification states with intense pulsed electron beam according to different regimes have been carried out. It is shown, that in mode of partial melting of the irradiation surface modification process of silicon plates is accompanied by the formation of numerous large micropores along the boundary plate/matrix and microcracks located in the silicon plates. A multi-modal structure (grain size within 30...50 μm with located on the boundaries silicon particles up to 10 μm) is formed in stable melting mode, as well as subgrain structure in the form of crystallization cells in size from 100 μm to 250 μm).

It has been established that the main cause of multiple increase of silumin fatigue life, processed with a pulsed electron beam, is the formation of the nanoscale multiphase structure in a modified surface layer.

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