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Fractography of the fatigue fracture surface of silumin irradiated by high-intensity pulsed electron beam

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Abstract. Irradiation mode has been revealed allowing to increase the silumin fatigue service life in three times, it was established that this fact is caused by the formation of multi-modal, multi-phase, submicro - and nano-structure able to lead to a significant increase in the critical length of crack.

1. Introduction

Fatigue fracture of the material [1] is the most frequent cause of failure of equipment, machinery, vehicles and construction. In this respect, it is important to prevent fatigue fracture (increase of service life) of critical parts, especially in those industries where occurrence of accidents leads to disastrous consequences. Fatigue cracks originate usually in the surface layer of a part [2]. A highly effective method of surface modification of parts and, increase of their fatigue life [3-5] consequently, is a material treatment by intensity pulsed electron beam allowed to modify the structure of the surface layer of tens of micrometers in thickness, turning it into a multi-modal structural-phase state and almost without changing the structural-phase state of the main volume of the alloy. [6-10]. The aim of this work is the analysis of regularities of a silumine structure modification with high-intensity pulsed electron beam, determination of mechanisms responsible for the fracture of silumin subjected to high-cycle fatigue testing.

2. Materials and methods of study

Silumin of a grade AK12 [11] was used as a material for study. Fatigue tests were carried out on a special installation according to the scheme of an asymmetrical cantilever bending [12]. 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" (IHCE SB RAS) [8] 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/cm²; 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



(device Microvisor metallographic μ Vizo - MET-221) and scanning electron microscopy (device LEO EVO 50).

3. Experimental results and their discussion

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 (Figure 1).

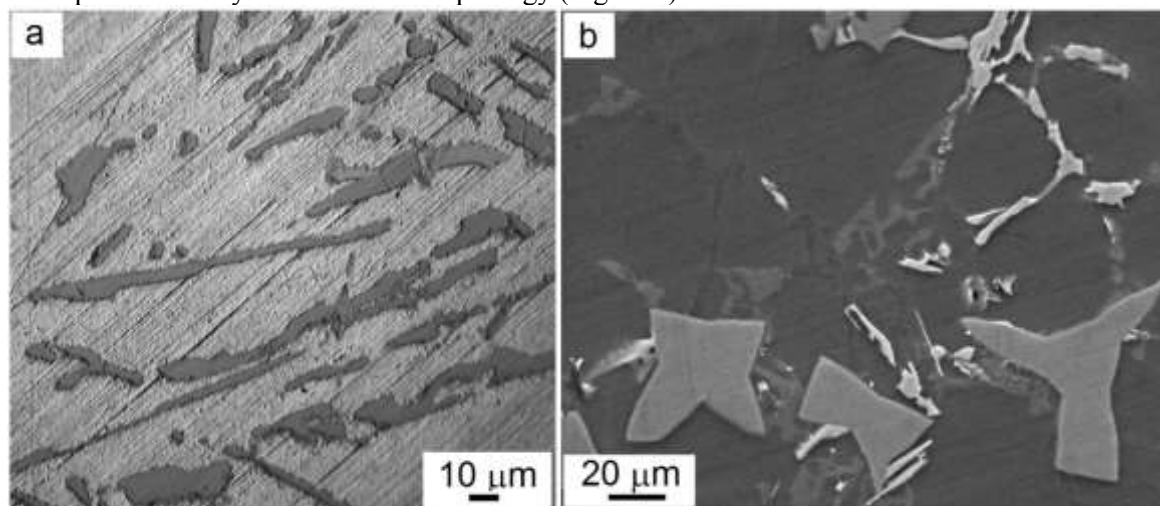


Figure 1. Structure of silumin of the original state (before intense electron beam irradiation); a - optical microscopy; b – scanning electron microscopy.

The irradiation of silumin surface by intensive pulsed electron beam with a submillisecond duration of exposure depending on the electron beam energy density is accompanied by melting of the sample surface (Figure 2, a, b), or by melting of the material layer surface of some thickness (unit - tens of micrometers) (Figure 2, c, d).

In the first case, the modification process of silicon plates is accompanied by the formation of numerous micropores along the boundary plate/matrix, and micro-cracks located in the silicon plates (Figure 2, b). It is evident, while subsequent fatigue testing silicon plates will be stress concentrators (sources of microcracks). In the second case the structure of the surface layer is fundamentally different on morphological grounds from the structure of the original sample (Figure 1) and the sample irradiated in mode of the surface melting (Figure 2, a, b). Homogeneous grain structure (grain size of eutectic varies within 30...50 μm) (Figure 2, c, d) is formed on the irradiation surface. Silicon in the form of layers or separate particles of globular form is situated at grain boundaries, the transverse dimensions of which do not exceed 10 μm. Stress concentrators which can cause the sample fracture are not detected on the irradiation surface.

Indeed, our tests revealed a significant dependence of the fatigue durability value on the irradiation mode of the silumin samples surface. While the irradiation mode leading to a partial melting of the sample surface (Figure 2, a, b), the fatigue life was below the fatigue durability of the original samples in some cases. When the irradiation of the surface layer in a stable melting mode with a forming on the surface of the grain of a structure with globular inclusions of silicon (Figure 2, c, d), fatigue life of silumin samples exceeded the fatigue life of the source material more than in 3 times.

Made assumptions about possible causes of low fatigue life of the samples irradiated by electron beam in mode 15 j/cm²; 150 μs; 3 pulses, were confirmed while analyzing of a silumin surface fracture by scanning electron microscopy.

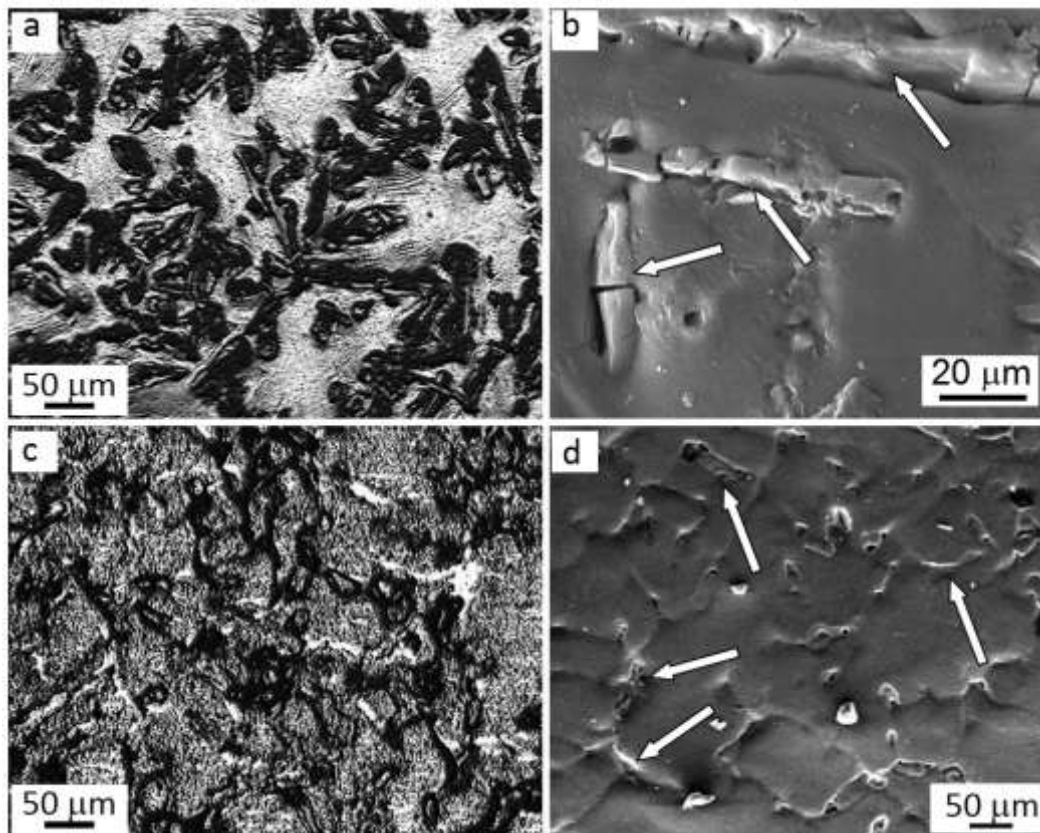


Figure 2. Surface structure of silumin irradiated by electron beam in modes: 15 j/cm²; 150 μs; 3 pulses (a and b) and 20 j/cm²; 150 μs; 5 pulses (c, d); a, c – optical microscopy; b, d – scanning electron microscopy; silicon particles are arrowed on (b, d).

The electron-microscopic image of the fatigue fracture surface of the silumin sample treated by an electron beam according to mode 15 j/cm²; 150 μs; 3 pulses with fatigue life below the fatigue durability of the source material is shown on the Figure 3. It is impressive to see (Figure 3, a, b, the area of the crack formation is framed), that the fatigue crack is formed on the sample surface. Coarse inclusions of silicon located on the sample surface (Figure 3 c, the area of the material with a broken silicon plate is arrowed) are reasons for the formation of fatigue cracks. As was mentioned above, original layer structure of silicon on the treated surface does not change practically when the specified irradiation mode.

Fatigue fracture surface analysis of the sample irradiated by the electron beam in the mode of 20 j/cm²; 150 μs; 5 pulses, showed that the thickness of the melted layer varies in the range up to 20 μm (Figure 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 (Figure 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 (Figure 4, b).

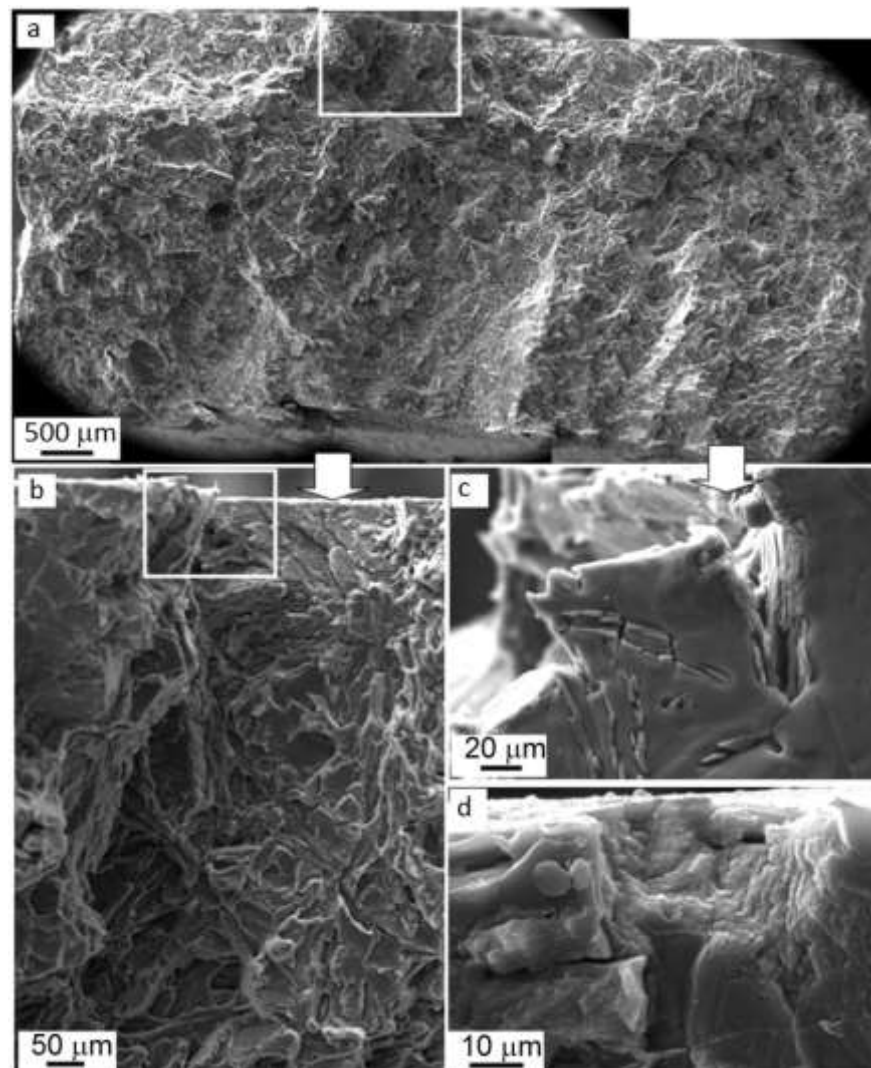


Figure 3. An electron microscope image of failure surface structure (a, b, d) and irradiation surface (b) of silumin treated by electron beam in mode 15 j/cm^2 ; 150 μs ; 3 pulses; on (a) and (b) the area of the crack formation is framed, on (b) – irradiation surface and on (c) – site of the fatigue crack formation are arrowed.

It is evident, that the formation of such submicro - and nano-phase structure is a determinant cause providing multiple increase of fatigue durability of silumin. The physical significance of the formation of multi-level structural-phase states consists in decrease of the scaling localization level of a plastic deformation in the surface layer, leading to a more even distribution of elastic stresses in a more significant volume of material when an external mechanical or thermal effects on the surface. Consequently, the generation energy in the surface layer of stress concentrators increases greatly, and the probability of formation in the surface layer of the defective substructure decreases. In other words, the formation of multi-level structural-phase state determines the manifestation in the surface layer of the modified silumin of damping properties with regard to the base material by external mechanical and thermal influences, preventing premature nucleation of fragile microcracks and their propagation from the surface into the main volume of material leading to the formation of the main cracks and fracture of the base material [13].

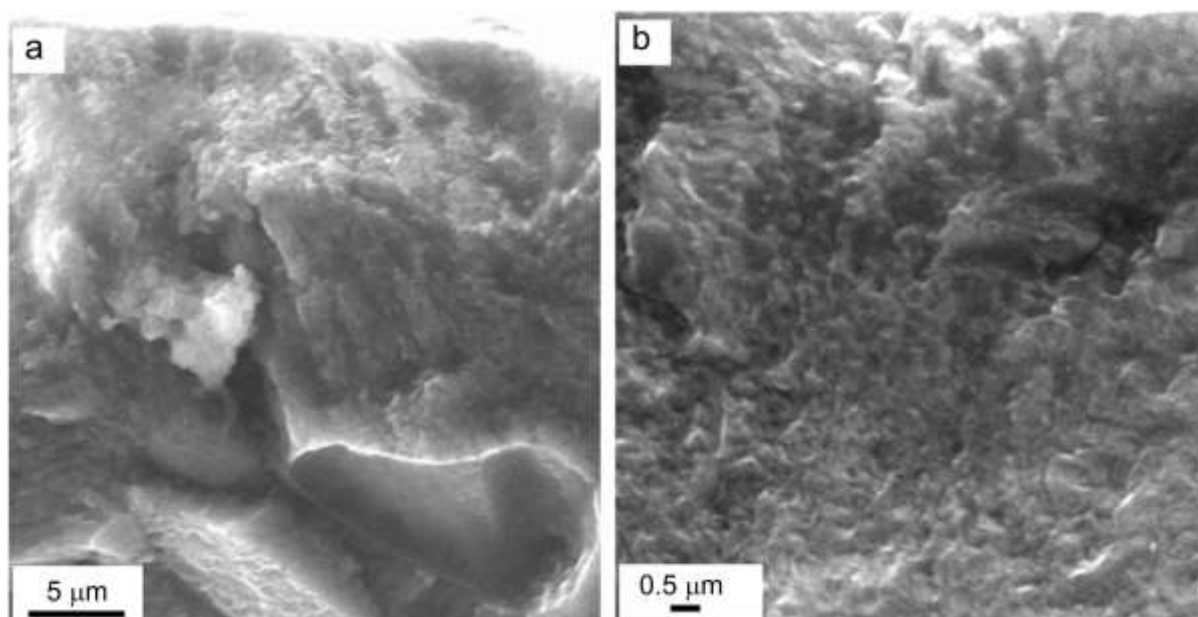


Figure 4. An electron microscope image of fatigue fracture surface of silumin treated in mode of irradiation by high –intensity pulsed electron beam 20 j/cm^2 ; 150 μs ; 5 pulses

4. Conclusion

The surface modification of the eutectic silumin by high-intensity pulsed electron beam has been carried out. High-cycle fatigue testing was performed and exposure mode allowed increase the material fatigue life more than three times was determined. Studies of the structure of the surface irradiation and surface fatigue fracture of silumin in the initial (unirradiated) state and after modification by intense pulsed electron beam was 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 $30\text{--}50 \text{ }\mu\text{m}$ with located on the boundaries silicon particles up to $10 \text{ }\mu\text{m}$) is formed in stable melting mode, as well as subgrain structure in the form of crystallization cells in size from $100 \text{ }\mu\text{m}$ to $250 \text{ }\mu\text{m}$). An assumption was made that formation of a multi-modal, multi-phase, submicro- and nano- sized structure assisting to a significant increase in the critical length of the crack is a main reason for the increase of the silumin fatigue life.

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