Fatigue life of silumin irradiated by high intensity pulsed electron beam

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Abstract. The electron-beam processing of silumin, leading to the evolution of structure-phase state of its surface is carried out. It has been shown that this alloy is a multiphase material and contains, except an aluminum-based phase, the particles of intermetallic compounds of Al-Si-Fe-Mn. It is shown that electron beam treatment of the eutectic silumin surface increases the fatigue service life more than in 3.5 times. The analysis of structure-phase states modification of silumin subjected to electron beam treatment with the following fatigue loading up to the failure is carried out by methods of optical and scanning electron diffraction microscopy. Analysis of the surface layer structure revealed the sources of nucleation of submicrocracks. It is revealed that the large silicon plates located on the surface and in the subsurface layer are the most dangerous stress concentrators.

1. Introduction
Fatigue failure of parts is one of the most commonly occurring causes of equipment, machinery, vehicles and structure failure. Therefore the problem of preventing the fatigue failures (service life increase) of critical parts is a very important one, especially in the branches of industry where the occurrence of emergencies leads to disastrous consequences. As a rule, fatigue cracks are initiated in the surface layer of the part. Therefore, the state of the surface layer affects significantly the fatigue life of the material.

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 relatively low specific gravity. However, the relatively low strength properties of silumin narrow significantly its scope of application. The most important method of improving their mechanical properties is the modification [1, 2].

The effective method of the specified modification and as a consequence, fatigue life increase is the processing of material surface by high intensity electron beam of submillisecond effect duration allowing to change the surface layer structure tens of micrometers thick transforming it into multimodal structure-phase state and essentially without changing the structure-phase state of the alloy basic volume [3-5].
In papers [6-8] it was shown that surface treatment of stainless steels with high intensive pulsed electron beam is accompanied by increase (more than by 3.5 times) in fatigue life of these materials. It is obvious that deformation effect taking place under fatigue tests is favorable for structural transformation of material.

The aim of this work is to analyze the regularities of structure modification silumin by high-intensity pulsed electron beam, subjected to high-cycle fatigue testings up to the fracture.

2. Materials and research methods

Al-Si alloy (silumin) in an as-cast condition has been used as the material of the research. Pulsed melting of the silumin surface layer has been carried out by high-intensity pulsed electron beam on the installation «SOLO». Processing modes: electron energy is 18 keV, energy density of electron beam is \((10–25) \text{ J/cm}^2\), effect pulse duration is 50 and 150 \(\mu\text{s}\), the number of effect pulses is 1, 3, 5; pulse recurrence frequency is 0.3 \(\text{s}^{-1}\); irradiation has been carried out in argon at a residual pressure of 0.02 Pa. These modes have been provided to heat the surface layer of a thickness of 50 \(\mu\text{m}\) up to melting temperature and quenching from the melt at speeds up to 10\(^6\) \(\text{K/s}\).

Fatigue tests, as in [6-8], have been performed on a special installation according to the scheme of a circular asymmetric cantilevered bending. The samples have had the shape of a parallelepiped with dimensions of 8x14x145 mm. The simulation of cracks has been carried out by a cut in the form of a semicircle with a radius of 10 mm. Test temperature is 300 K, the frequency of sample loading with curve is 15 Hz, the load is 10 MPa. At least 5 samples have been tested for each irradiation mode.

Investigation of the structure and phase composition of the alloy has been carried out by the methods of optical (etched thin section) and scanning electron microscopy (SEM). The elemental analysis has been carried out by the methods of electron micro-X-ray spectral analysis.

3. Results and their discussions

Figure 1 provides the image of the structure of the aluminum-silicon alloy in an initial state, obtained by the methods of scanning electron microscopy in inversely reflected electrons. It is evident that the alloy is a multiphase material. The selection of the second phases has predominantly a platelet form, and may differ significantly in intensity. The main volume of the inclusions of the second phase has a low intensity and is slightly different in intensity from the matrix image. It is known that the inclusions formed by the atoms of higher atomic weight, reflect the incident flux of electrons more intensively. Therefore, they have a lighter contrast in the images of the structure obtained in the inversely reflected electrons [9]. This fact allows concluding that the inclusions detected in the alloy differ significantly in elemental composition. In addition to the plates, there are also formations in the form of polyhedrons and selections of irregular shape in the alloy.

The main elements of the researched alloy are aluminum and silicon, which concentration in average is equal to 10.5 mass %. For elemental analysis three types of particles have been selected. They are differ in the intensity of the image in the inversely reflected electrons and morphology (Fig. 1, c). Analyzing the results presented in Table 1, it can be noted that in the investigated alloy, along with aluminum and silicon, there are iron and manganese, distributed extremely unevenly along the volume of the material. The matrix (spectrum 1), within the sensitivity of the analyzer, is formed by aluminum. Particles, having relatively low contrast in the images of the patterns in the inversely reflected electrons, are generated by the atoms of silicon (spectrum 2). Particles with brighter phase contrast contain atoms of aluminum, silicon, iron and manganese (spectrum 3 and spectrum 4).

The morphology of the particles is determined by the relative concentration of atoms of iron and silicon in them. Namely, in the particles in the form of “skeletons” (spectrum 3) the concentration ratio is \(\text{Al/Fe/Si} = 7/4/1\); in the particles of a plate-like morphology (spectrum 4) the concentration ratio is \(\text{Al/Fe/Si} = 3/2/1\). Following the results, represented in [1, 10], it can be supposed that the particles of a plate-like morphology (spectrum 4) are \(\beta\)-phase; its structure is defined as \(\text{Al}_5(\text{Fe, Mn})\text{Si}\); the particles of a skeletal form (spectrum 3) are \(\alpha\)-phase; its structure is defined as \(\text{Al}_6(\text{Fe, Mn})\text{Si}\). Silicon and
intermitallide particles have plate-like and skeletal forms. Therefore, they can be a source of cracks in mechanical testing of the material.

![Figure 1](image)

**Figure 1.** The structure of aluminum-silicon alloy (initial state). (a, b) – SEM analysis of the surface in inversely reflected electrons, (c) – surface image, obtained by micro-X-ray spectral analysis; on (c) the areas, which are chosen for the material elemental analysis, are indicated.

**Table 1.** Results of the micro-X-ray spectral analysis of the section of aluminum-silicon alloy surface represented on Fig. 1.

| Element, mass % | Number of the section |
|-----------------|-----------------------|
|                 | 1    | 2    | 3    | 4    |
| Al 99           | 2.0  | 57   | 54   |
| Si 1.0          | 98   | 8    | 15   |
| Mn 0.0          | 0.0  | 1    | 1    |
| Fe 0.0          | 0.0  | 34   | 30   |

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 [11]. 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. 2 with the parameters of irradiation – 20 J/cm^2; 150 μs; 0.3 s^-1; 5 pulse.

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. 1 with the parameters of irradiation – 15 J/cm^2; 150 μs; 0.3 s^-1; 3 pulse) and maximum (for mode No. 2) 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.

The irradiation of silumin surface for mode No. 1 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. 2, b).

During silumin irradiation with high-intensity electron beam in mode No. 2 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. 4, a-c), and the thickness of the molten layer varies in the range up to 20 μm (Fig. 4, d).

Resulting from high-speed crystallization a multimodal structure at the macro level is represented by the grains on the basis of aluminum, whose dimensions range from 30 to 50 μm. There are silicon particles on the grain boundaries; their transverse dimensions do not exceed 20 μm (Fig. 4, b). Mesolevel of the modified layer consists of two-phase (silicon and solid solution on the basis of aluminum) crystallization cells detected on the surface of a fatigue fracture. The cell crystallization sizes vary in the range of 100 nm up to 250 nm (Fig. 4, e). 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.

Figure 3. Electron microscope image of the fracture surface structure (a, b) and irradiation surface (b) of silumin, processed by electron beam according to mode No. 1. 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

Figure 4. Electron microscope image of irradiation surface structure (a-c) and silumin fracture surface (d, e), processed by electron beam according to mode No. 2. The pointers on (b) indicate silicon particles; on (c) – edge of the sample fatigue fracture

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. Thus, the formation of a submicro- and nanoscale multiphase structure at the irradiation of silumin according to mode No. 2 is also the defining reason assisting a multiple increase of its fatigue life.

4. Conclusion

Processing of silumin by high intensive electron beam has been carried out. It has been established that the fatigue tests of silumin subjected to irradiation with high intensity pulsed electron beam resulting in the increase in fatigue life by more than 3.5 times. Investigations of structure and surface modified layer destruction of silumin subjected to high-cycle fatigue tests to fracture have been carried out by methods of optical and scanning electron microscopy.

It has been shown that this alloy is a multiphase material and contains, except an aluminum-based phase, the particles of intermetallic compounds of Al-Si-Fe-Mn. These particles have a plate or skeletal form and therefore, can be a source of cracks in the material mechanical testing. The researches of an irradiation 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 has been established that the main reason of multiple increase of silumin fatigue life, irradiated by a pulsed electron beam, is the formation of the submicro- and nanoscale multiphase structure in a modified surface layer.

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