

## Fractography of Fatigue Fracture Surface in Silumin Subjected to Electron-Beam Processing

S V Konovalov<sup>1</sup>, K V Aksenova<sup>1</sup>, V E Gromov<sup>1</sup>, Yu F Ivanov<sup>2,3</sup> and O A Semina<sup>1</sup>

<sup>1</sup>Siberian State Industrial University, Novokuznetsk, Russia

<sup>2</sup>Institute of High Current Electronics Siberian Branch of Russian Academy of Science, Tomsk, Russia

<sup>3</sup>National Research Tomsk Polytechnic University, Tomsk, Russia

E-mail: konovserg@gmail.com

**Abstract.** The surface modification of the eutectic silumin with high-intensity pulsed electron beam has been carried out. Multi-cycle fatigue tests were performed and irradiation mode made possible the increase in the silumin fatigue life more than 3.5 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 with intense pulsed electron beam were carried out by methods of scanning electron microscopy. It has been shown, that in mode of partial melting of the irradiation surface the 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  $\mu\text{m}$  with silicon particles up to 10  $\mu\text{m}$  located on the boundaries) is formed in stable melting mode, as well as subgrain structure in the form of crystallization cells from 100 to 250  $\mu\text{m}$  in size). Formation of a multi-modal, multi-phase, submicro- and nanosize structure assisting to a significant increase in the critical length of the crack, the safety coefficient and decrease in step of cracks for loading cycle was the main cause for the increase in silumin fatigue life.

### 1. Introduction

One of the most widespread causes of equipment, mechanisms, machines and structures failure is fatigue fracture of parts. In this connection, prevention of fatigue fracture of critical parts and, consequently, increase in their service life is an urgent problem [1]. Process of fracture begins, as a rule, with appearance of microscopic cracks which when developed result in complete fracture of article [2]. Fatigue cracks initiate in near-surface layer in zone of action of stress concentrators that may be inclusions of the second phase, micropores, scratches and dents. Therefore, in the process of fatigue fracture the state of material surface layer and its processing with hardening capable of significant increase in fatigue life of material [2] play the essential part.

Effective method of surface hardening of metals and alloys and, as a consequence, increase in fatigue service life is material's surface processing with high-intensity electron beam of submillisecond duration. This method enables change in structure of tens micrometers thick surface layer by transforming it into multi-modal structure-phase state with practically unchanged structure-phase state of the main volume of the alloy [3, 4].



The use of electron beams as a means of metals and alloys modification results in significant change in structure-phase state of surface layers and, as a consequence, increase in corrosion resistance, wear resistance and microhardness, unattainable in conventional methods of surface processing [5-10].

The purpose of the research is to analyze the modification features of silumin structure with high-intensity pulsed electron beam, detection of mechanisms responsible for fracture of silumin subjected to multi-cycle fatigue tests.

## 2. Material and methods of research

Test material was Al-Si alloy (silumin) (Al – 89.77, Si – 9.88, Fe – 0.35, wt. %). Fatigue test of  $8 \times 14 \times 145$  mm samples were done on the special setup according to cyclic asymmetrical cantilever bending scheme [1]. Simulation of crack was performed with half circle notch of 10 mm radius. At the test temperature 300 K frequency of samples bending cyclic amounted to 15 Hz under 10 MPa load.

Irradiation of samples surface for fatigue tests was performed on the setup "SOLO" [2] with the following parameters: electron energy  $U = 18$  KeV; pulse repetition frequency  $f = 0.3$  Hz; pulse duration of electron beam  $\tau = 150$   $\mu$ s; energy density of electron beam  $E_s = 15$  and  $20$  J/cm<sup>2</sup>; number of pulse of action  $N_1 = 3$  and  $N_2 = 5$ . The face surface of samples was irradiated i.e. the surface being located above the crack simulating notch. Not less than five samples were tested by each mode of irradiation. Studies of irradiation and fracture surface were performed with methods of scanning electron (setup SEM-515 Philips) microscopy.

## 3. Results and their discussions

Fatigue life tests of silumin irradiated samples revealed a very wide spectrum of results whose values depend significantly both on material structure and electron-beam irradiation mode and they differ by more than order of magnitude (from 132000 to 517000 cycles up to fracture) [11, 12]. Maximum fatigue life increase (~by a factor of 3.5) provided the irradiation mode with high-intensity pulsed electron beam with parameters  $20$  J/cm<sup>2</sup>;  $150$   $\mu$ s; 5 pulses.

The distinctive feature of test silumin in the initial state is presence of a large number of silicon inclusions of platelet shape predominantly. Plates locate chaotically or decorate the grain boundaries of the alloy. Plate sizes of silumin under study vary in the range from units to tens of micrometers. Irradiation of silumin surface with high-intensity pulsed electron beam depending on energy density of electron beam is accompanied by either melting of sample surface ( $15$  J/cm<sup>2</sup>;  $150$   $\mu$ s; 3 pulses – the first mode) or melting of material surface layer of thickness from units to tens of micrometers ( $20$  J/cm<sup>2</sup>;  $150$   $\mu$ s; 5 pulses – the second mode).

Electron-beam processing (EBP) according to the mode No.1 initiating the starting stage of silicon inclusions melting results in the running of two interconnected processes: globularization of silicon inclusions (Fig. 1, a) and brittle destruction of silicon plates (Fig. 1, b). Plate destruction process is accompanied by the formation of numerous micropores located along the interface plate/matrix and microcracks located in silicon plates (Fig. 1, b). In the micrograph of fatigue destruction surface it is seen that fatigue crack forms on the sample surface (Fig. 1, c). The large silicon plates located on the surface (Fig. 1, a) and in near-surface sample layer (Fig. 1, f) being critical stress concentrators are responsible for fatigue crack formation. As a result the fatigue tests with 180000 cycles resulted in plate destruction (Fig. 1, d) and formation of extended microcracks (Fig. 1, e). Thus, formation of micropores and microcracks in surface layer weakens the material in electron-beam processing in the mode No. 1. It is the determining factor facilitating only insignificant increase in fatigue life of material.

Electron-beam processing according to the mode No.2 initiating high-speed melting and subsequent high-speed crystallization results in significant structure refinement of silumin sample surface (Fig. 2). According to morphological attributes the surface layer structure differs from structure of initial sample and the sample irradiated by the mode No. 1. A homogeneous structure of granular (cellular) type forms on the surface of irradiation (Fig. 2, a, b). Regions with sizes from 30 to

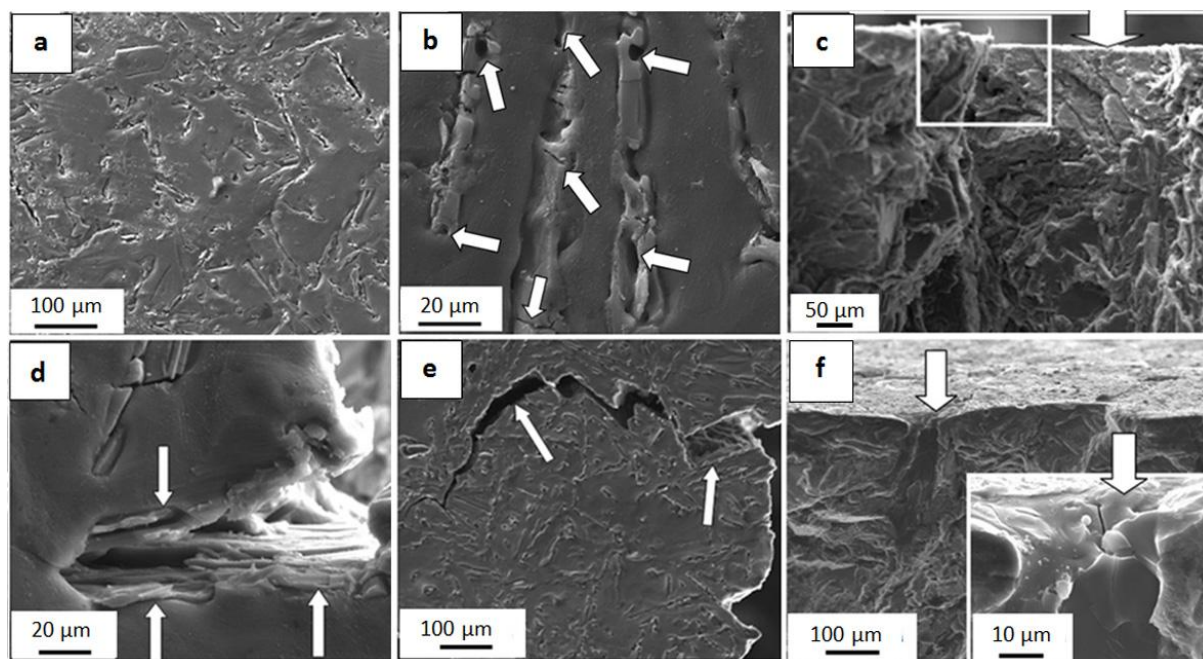


Fig. 1. Surface structure of silumin sample processed with electron beam according to the mode No. 1 and fractured after 180000 cycles. a, b – state prior to fatigue tests; c-f – post-fatigue tests states. Arrows designate: in (b) – micropores and microcracks in silicon plates; in (c) – surface of irradiation (area of fatigue crack formation); in (d) – silicon plates fractured in the process of fatigue tests; in (e, f) – microcracks having been formed in fatigue tests.

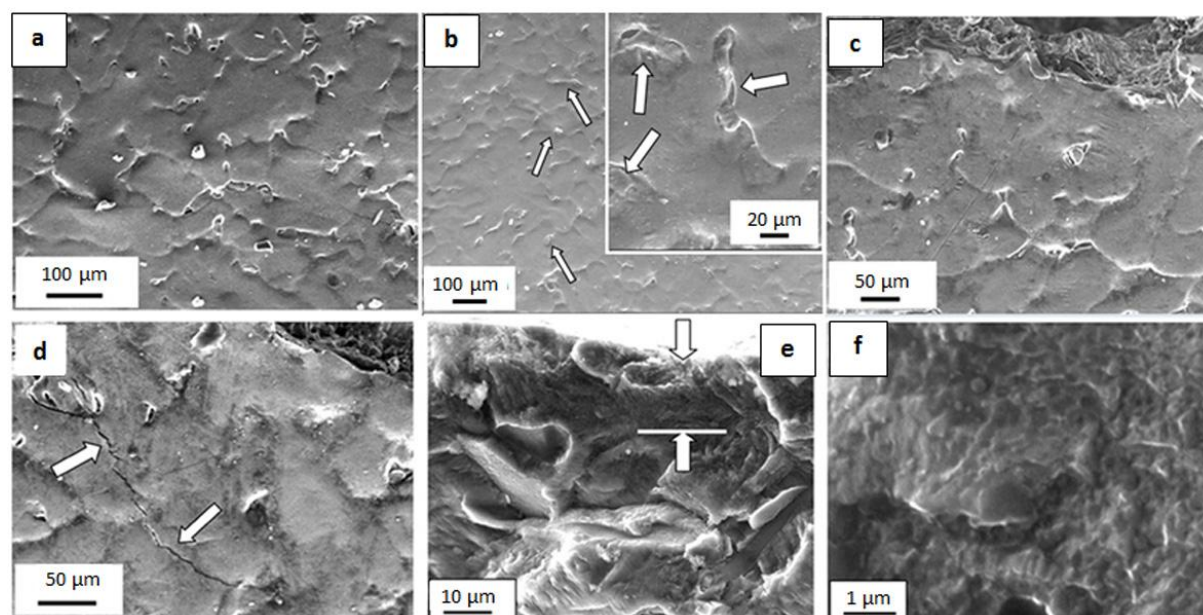


Fig. 2. Surface structure of silumin sample processed with electron beam according to the mode No. 2 and fractured after 517000 cycles. a, b – state prior to fatigue tests; c-f – post-fatigue tests states. Arrows designate: in (b) – silicon particles; in (d) – microcrack having been formed in the process of fatigue tests; in (e) – silumin layer thickness melted with electron beam.

50  $\mu\text{m}$  are separated by silicon interlayers whose transverse sizes do not exceed 10  $\mu\text{m}$  (Fig. 2, b). Thickness of melted layer varies within 20  $\mu\text{m}$  (Fig. 2, e). It is important that stress concentrators capable of being sample fracture sources are not observable on the edges of fracture (Fig. 2, c). The cracks parallel to fracture surface locate at some distance from it (Fig. 2, d). It is evident that the concentrator having been the cause of sample fracture located under the surface, most probably, at the interface of liquid and solid phases.

High-speed crystallization results in two-phase subgrain structure (silicon and aluminium-based solid solution), whose cell sizes vary from 100 to 250 nm (Fig. 2, f). It is the formation of similar submicro- and nanosize multiphase structure in electron-beam processing according to the mode No. 2 that is the determining cause facilitating a multiple increase in its fatigue life.

The results of fractographic investigations allowed the analysis of fatigue fracture mechanisms of silumin samples subjected to electron-beam processing according to different modes. Polycrystalline character of structure (granular structure of aluminium-based solid solution and a large number of comparatively big silicon plates) results in multiple branching of material fracture front (Fig. 3, a-c). A large number of microscopically visible fracture traces located in parallel is formed which is especially characteristic for samples with maximum number of cycles up to fracture (Fig. 3, c). It is determined that in silumin under study a mixed mechanism of fatigue fracture is realized. Microrelief of fatigue fracture is presented by pits of ductile fracture and quasi-cleaved facets. Pits are dominant element of fracture surface structure and they form as a result of cutting of micropores through which aluminium grain fracture occurred (Fig. 3, d). Silicon plates fail according to cleavage mechanism (Fig. 3, e).

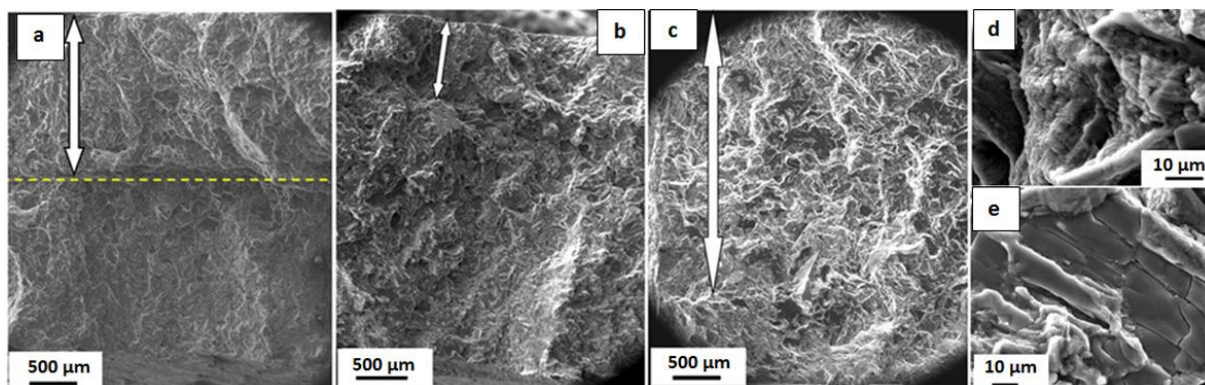


Fig. 3. Fractography of fatigue fraction surface of silumin samples. A, B – initial state, 130000 cycles; b – electron-beam processing according to the mode No.1, 180000 cycles; c – electron-beam processing according to the mode No.2, 517000 cycles. Arrows designate the fatigue crack growth zone.

On the surface of fatigue fracture of silumin samples three distinctive zones are revealed – zone of crack fatigue growth, zone of finish breaking and zone of accelerated crack growth separating them [13]. Deformation processes proceeding in fatigue tests of the material develop, in full measure, in zone of crack fatigue growth and essentially to a lesser degree, in zone of finish breaking. The width of zone of crack fatigue growth in silumin samples under study is correlatively connected with number of cycles up to fracture, i.e. it depends on material irradiation mode with electron beam. Width of zone of crack fatigue growth is taken equal to critical length of crack [1]. When analyzing Table 1 it is seen that electron-beam processing according to the mode No. 2 allows the increase in critical crack length by a factor of 2 thereby increasing the service life of material working capacity.

From the magnitude of ratio of fatigue growth zone area to area of zone occupied by finish breaking it can be judged on the value of safety coefficient of the given material: the less this ratio, the lower the safety coefficient at the same load intensity of fatigue tests [14]. Electron-beam processing



according to the mode No. 2 increases safety coefficient (by a factor of 1.6) of material operation (Table 1).

Fatigue striations being a trace of crack displacing for one step in every loading cycle belong to the important indication of fatigue destruction zone of the material [1, 13, 14]. The distance between striations is determined by the capacity of the material to withstand the propagation of fatigue crack: the less distance between striations, the larger the resistance of the material to crack propagation. It is seen from Table 1 that crack step in one cycle of fatigue loading in silumin samples processed according to the mode No. 2 is less by a factor of  $\sim 2.7$ , consequently, the given samples have a markedly higher resistance to fatigue crack propagation.

Table 1. Surface parameters of silumin fatigue fracture.

Mode of EBP	Width of crack fatigue zone, mm	Safety coefficient	Crack step, $\mu\text{m}$
Without EBP, 130000 cycles	1.80	0.53	0.75
15 J/cm <sup>2</sup> ; 150 $\mu\text{s}$ ; 3 pulses; 180000 cycles	0.75	0.24	0.95
20 J/cm <sup>2</sup> ; 150 $\mu\text{s}$ ; 5 pulses; 517000 cycles	3.50	0.86	0.28

#### 4. Conclusion

It is shown that different states of structure form in silumin surface layer depending on the parameters of electron-beam processing. In electron-beam processing according to the mode No. 1 initiating the starting stage of silicon inclusions melting the formation of highly defective surface layer containing micropores and microcracks weakening the material are observed. In electron-beam processing according to the mode No. 2 initiating a high-speed melting and subsequent high-speed crystallization the structure of cellular type with silicon in the form of extended nanosize interlayers or globular shape inclusions is formed in up to 20  $\mu\text{m}$  thick near-surface layer.

Analysis of fatigue fracture mechanisms of silumin samples subjected to electron-beam processing according to different modes was carried out. It was detected that large silicon plates of micron and submicron sizes being undissolved in electron-beam processing were the sources of fatigue microcracks.

Surface irradiation of silumin samples with electron beam according to the optimal mode No. 2 allows (1) the increase in critical crack length by a factor of 2 thereby increasing the service life of material working capacity; (2) the increase in safety coefficient of material operation by a factor of 1.6; (3) the decrease in crack step in one cycle of fatigue loading by a factor of 2.7 which is indicative of a higher resistance to fatigue crack propagation.

It was determined that the main causes of increase in fatigue life of silumin irradiated with high-intensity pulsed electron beam were the formation of multiphase submicro- and nanosize structure in the surface layer and refining of large silicon plates.

*This work has been supported by a grant of the President of the Russian Federation for state support of young Russian scientists – Doctors of Sciences (project MD-2920.2015.8) and state task No 3.1496.2014/K.*

#### References

- [1] Kotsan'da S 1990 *Fatigue cracking of metals* (Moscow: Metallurgiya).
- [2] Gromov V E, Ivanov Yu F, Vorobiev S V and Kononov S V 2015 *Fatigue of steels modified by high intensity electron beams* (Cambridge: Cambridge International Science Publishing Ltd).
- [3] Engelko V, Yatsenko B, Mueller G and Bluhm H 2001 *Vacuum* **62/2 (3)** 211.
- [4] Proskurovsky D I, Rotshtein V P, Ozur G E, Ivanov Yu F and Markov A B 2000 *Surf. and Coat. Technol.* **125** 49.
- [5] Hu J J, Zhang G B, Xu H B and Chen Y F 2012 *Materials Science and Technology* **27 (4)** 300.
- [6] Hao S Z, Qin Y, Mei X X, Gao B, Zuo J X, Guan Q F, Dong C and Zhang Q Y 2007 *Surf. and*

- Coat. Technol.* **201** 8588.
- [7] Dong C, Wu A, Hao S [et. al.] 2003 *Surf. and Coat. Technol.* **163-164** 620.
- [8] Zhang K M, Zou J X, Grosdidier T [et. al.] 2008 *The European Physical Journal: Applied Physics* **43 (3)** 343.
- [9] Hao Y, Gao B, Tu G F, Cao H, Hao S Z and Dong C 2012 *Applied Surface Science* **258** 2052.
- [10] Hao Y, Gao B, Tu G F [et. al.] 2011 *Materials Science Forum* **675-677** 693.
- [11] Konovalov S V, Alsaraeva K V, Gromov V E, Ivanov Yu F and Semina O A 2016 *Key Engineering Materials* **675-676** 655.
- [12] Ivanov Yu F, Alsaraeva K V, Gromov V E, Popova N A and Konovalov S V 2015 *J. of Surf. Investigation. X-ray, Synchrotron and Neutron Techniques* **9 (5)** 1056.
- [13] Fellouz Dz. 1982 *Fractography and atlas of fracture patterns* (Moscow: Metallurgiya).
- [14] Terentév V F 2003 *Fatigue of metallic materials* (Moscow: Nauka).