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Fatigue variation of surface properties of silumin subjected to electron-beam treatment

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Abstract. 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 transmission electron diffraction microscopy. The tribology and strength properties of silumin surface after electron beam treatment and fatigue tests are studied and hardness decrease, wear coefficient and friction coefficient increase with the growth of cycles number are revealed. The possible reasons of the tribology and strength properties of silumin surface layers decrease are discussed.

1. Introduction

Concentrated flows of energy are used currently for increasing the mechanical and service properties of steels and alloys. An exposure to their effect the ultrahigh speed heating, melting, evaporation, crystallization and subsequent cooling of the material are realized. In total, these processes result in the formation of wide spectra of amorphous, nano-, submicro- and microcrystalline structures being accompanied by multiple increase in physico-chemical and mechanical properties of material which are often beyond the reach of the conventional methods of surface processing [1-3].

Intensive pulsed periodic electron beams are the exceptionally flexible surface source of dynamic thermal effect on materials. The main advantage of the method in question consists in combination of practically total absorption of energy of electrons and three-dimensional character of its liberation with the possibility of a rather wide variation of depth of electron's penetration in material and correspondingly, dynamics of thermal fields and parameters of stress wave. Nowadays due to the wide variation limits of beam energy density, duration of pulse and electron energy, they are the unique and highly effective tool for both the investigations of physical nature of formation of gradient structure-phase states in a solid body and purposeful modification of structure and properties of silumins in order to improve the service characteristics of products [4-6].

In a number of papers [1, 7] it was shown that surface processing of stainless steels with high intensity electron beam was accompanied by multiple (by more than 3.5 times) increase in fatigue life of these materials. It is apparent that deformation effect taking place in fatigue tests will be favorable to transformation of structure and properties of materials.

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Nowadays silumins find wide application in industry therefore the issues of increasing the mechanical and strength properties of silumins are especially urgent. The goal of the research was to study the change properties of silumin surface subjected to electron beam treatment (EBT).

2. Materials and methods of research

Al-Si alloy (silumin of eutectic composition) was used as test material. Fatigue tests were performed according to the scheme of asymmetric cyclic cantilever bending [1, 7]. Samples had the shape of parallelepiped with sizes of 8x14x145 mm. The imitation of a crack was done by the semicircle notch with 10-mm radius. Test temperature was 300 K, frequency of bend loading of samples was 15 Hz under load of 10 MPa.

The irradiation of samples surface prepared for fatigue tests were done on the device "SOLO" [8] with the following parameters: electron energy = 16 keV; pulse repetition frequency = 0.3 sec⁻¹; pulse duration of the electron beam $\tau = 150 \mu\text{s}$; number of pulse of effect $N = 1$ and 5; energy density of electron beam of $E_S = 20 \text{ J} \cdot \text{cm}^{-2}$. The face surface of samples was irradiated i.e. sample's surface located above the notch imitating a crack. For each mode of irradiation not less than five samples were tested. Strength properties of the material were studied by determining the nanohardness (Nano Hardness Tester NXT-S-AX-000X, load on indenter 5-300 mN). Investigations of wear rate of film-substrate system were done in disk-pin geometry by tribometer (CSEM, Switzerland) at room temperature and humidity. Volume of material's wear was determined after performance of profilometry of the formed track with the help of laser optic profilometer MicroMeasure 3D Station (Stil, France).

3. Results and discussion

In EBT of eutectic silumin in optimal regime a more than triple increase in fatigue life is attained [9]. The main reason of this effect is dispersion and quasihomogeneous distribution of silicon in the layer modified with EBT. EBT increases significantly the wear resistance of eutectic and hypereutectic silumins [10, 11]. The results of tribological tests of silumin are presented in table 1 and figure 1. The samples undergone the fatigue tests during 132000 cycles have the minimum wear coefficient. After 547000 cycles of fatigue tests the wear coefficient of the material increases, however, it remains lower in reference to coefficients registered for the initial material (unirradiated material before fatigue tests). The value of friction coefficient is similarly changed (table 1).

Table 1. Change of tribological parameters of silumin after irradiation and subsequent fatigue loading up to failure.

Regime of electron beam treatment (EBT)	Wear coefficient, Friction coefficient $10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$	
Initial state without EBT	8927	0.527
132000 cycles up to failure without EBT	13520	0.520
466000 cycles up to failure without EBT	13920	0.444
$20 \text{ J} \cdot \text{cm}^{-2}$; $150 \mu\text{s}$; 1 pulse. 132000 cycles up to failure	6466	0.457
$20 \text{ J} \cdot \text{cm}^{-2}$; $150 \mu\text{s}$; 5 pulses. 574000 cycles up to failure	8135	0.480

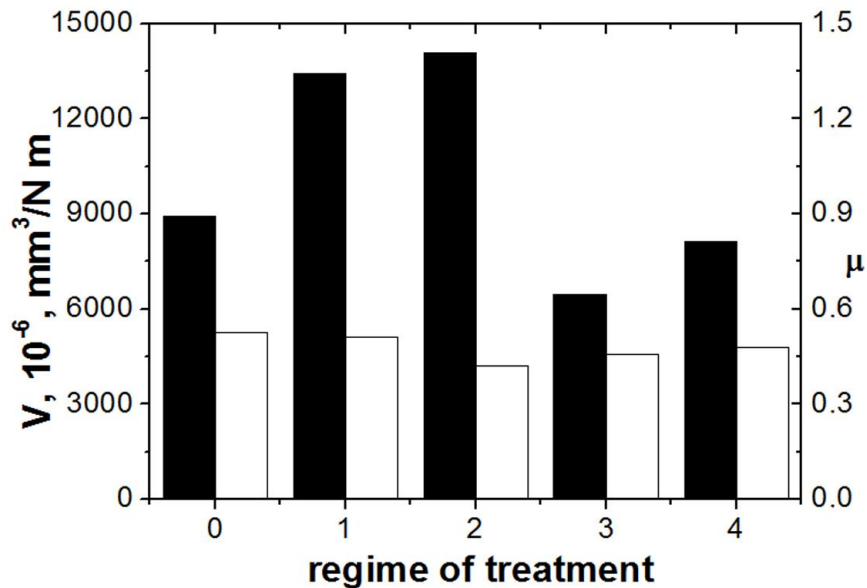


Figure 1. Values of wear coefficient V (dark columns) and values of friction coefficient μ (light columns) having place in different regimes of effect on silumin: 0 – silumin without irradiation (initial state); 1 – initial silumin after fatigue tests (130000 cycles); 2 – initial silumin after fatigue tests (466000 cycles); 3 – irradiation ($20 \text{ J} \cdot \text{cm}^{-2}$; $150 \mu\text{s}$; 1 pulse) and subsequent fatigue tests (130000 cycles); 4 – irradiation ($20 \text{ J} \cdot \text{cm}^{-2}$; $150 \mu\text{s}$; 5 pulses) and subsequent fatigue tests (466000 cycles).

The results of nanohardness tests are shown in figure 2. It is seen clearly that increase in cycles' number of fatigue loading by ~ 4.4 times results in reducing the hardness of surface layer by ~ 4.5 times. The value of Young modulus is changed similarly (figure 3): increase in cycles' number of fatigue tests results in multiple (by 3-4 times) decrease in Young modulus of surface layer of the material.

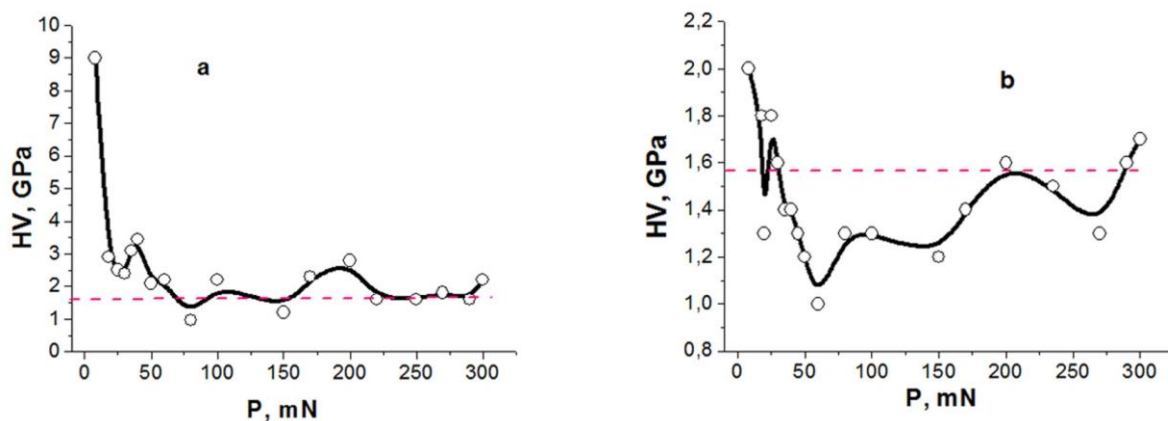


Figure 2. Dependence of hardness of silumin surface layer treated with high intensity pulsed electron beam and subjected to fatigue tests up to failure on the load to indenter; a – 132000 cycles; b – 574000 cycles.

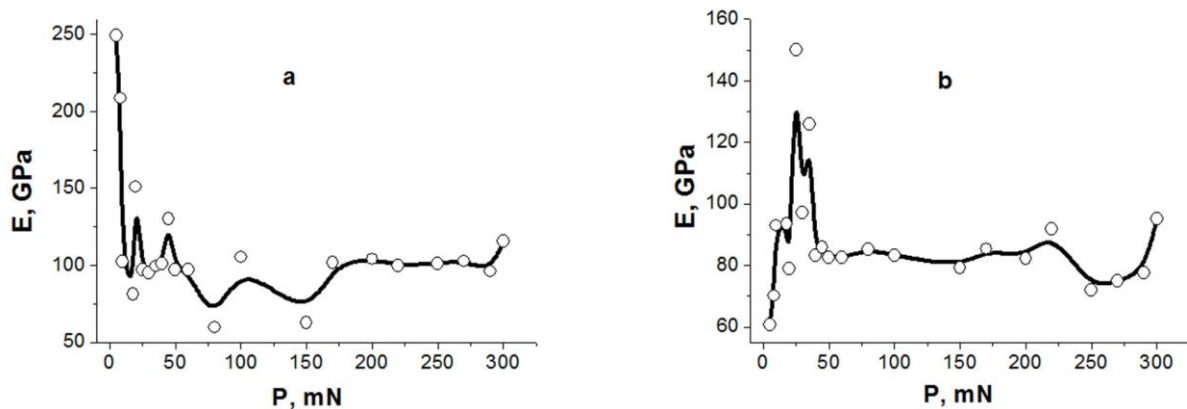


Figure 3. Dependence of Young modulus of silumin surface layer treated with high intensity pulsed electron beam and subjected to fatigue tests up to failure on the load to indenter; a – 132000 cycles; b – 574000 cycles.

It is evident that the similar changes of tribological and strength characteristics are caused by change in surface layer of silumin in the process of fatigue tests. The dependences of crystal lattice parameter of Al-based (a) and Si-based (b) solid solution on the regime of sample treatment (initial state and fatigue failed) determined by methods of X-ray and phase analysis are shown in figure 4.

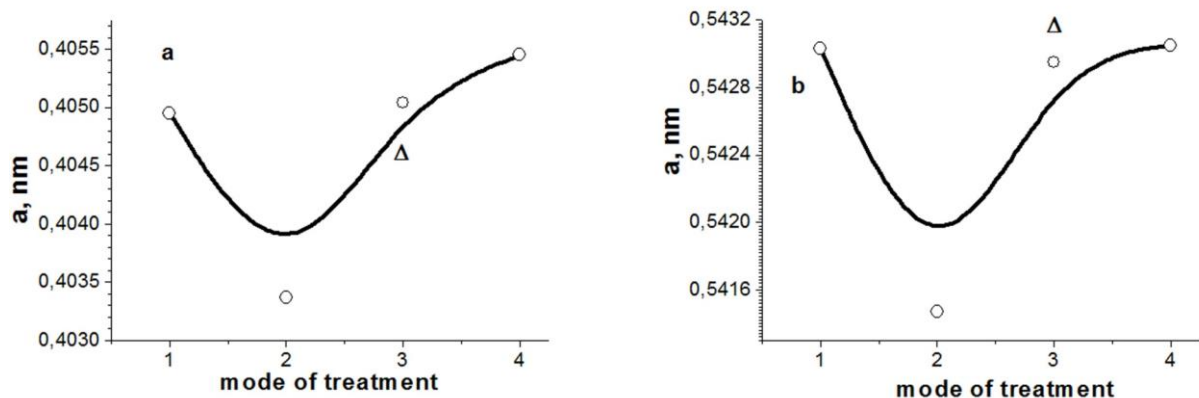


Figure 4. Dependence of lattice parameter of Al- based (a) and Si-based (b) solid solution on density of absorbed energy of electron beam. Regime of effect: 1 – silumin without irradiation; 2 – silumin without irradiation after fatigue tests (130000 cycles); 3 – after irradiation ($20 \text{ J} \cdot \text{cm}^{-2}$; $150 \mu\text{s}$; 1 pulse) and fatigue tests (132000 cycles); 4 – after irradiation ($20 \text{ J} \cdot \text{cm}^{-2}$; $150 \mu\text{s}$; 5 pulses) and fatigue tests (574000 cycles). Parameters of aluminium and silicon crystal lattice are designated by mark Δ , respectively for silumin irradiated according to the regime ($20 \text{ J} \cdot \text{cm}^{-2}$; $150 \mu\text{s}$; 1 pulse).

When analyzing the results shown in figure 4 it can be noted that maximum change of parameter of aluminium and silicon crystal lattice after fatigue tests was revealed in silumin untreated with electron beam. The decrease in parameter of aluminium crystal lattice in fatigue tests of initial samples (figure 4, a, regime 2) is connected, apparently, with the dissolution of silicon inclusions and penetration of silicon atoms into aluminium lattice. The radius of silicon atom is less than radius of aluminium atom by 0.0054 nm [12], therefore the concentration of Al-based solid solution with silicon atoms will be accompanied by the reduction of parameter of its lattice. The irradiation of silumin with electron beam at energy density $20 \text{ J} \cdot \text{cm}^{-2}$ results a relatively little decrease of parameter of aluminium crystal lattice and it is connected with dissolution of silicon particles and intermetallides phases, and concentration of solid solution with silicon atoms decreasing the parameter of aluminium crystal lattice and with

magnesium atoms having a larger, as compared to aluminium, atomic radius and, consequently, increasing the parameter of aluminium crystal lattice. Thus, electron beam treatment results in dissolution of Al- and Si-based phases and concentration of Al-based solid solution with these elements. The subsequent fatigue tests of silumin are accompanied by the additional increase of parameter of aluminium crystal lattice and it may be connected with the removal of silicon atoms from aluminium crystal lattice (effect of strain ageing of the material).

4. Conclusion

The fatigue tests of silumin subjected to irradiation with high intensity pulsed electron beam resulting in the increase in fatigue life by 3.5 time were carried out. Investigations of tribological and strength properties of silumin surface subjected to fatigue tests were performed and the decrease in hardness, the increase in wear coefficient and coefficient of friction with the increase in number of cycles of fatigue loading were revealed.

Acknowledgments

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