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Fatigue Life of Silumin Treated with a High-Intensity Pulsed Electron Beam

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Abstract—The regularities of the formation of the structure of silumin irradiated with a high-intensity electron beam in different modes are revealed using optical and scanning electron microscopy. The optimum irradiation mode that allows one to increase the fatigue life of this material by a factor of up to 3.5 is determined. The probable causes of the observed effect are investigated.

Keywords: silumin, high-intensity pulsed electron beam, structure, fatigue life

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1. INTRODUCTION

Silumins (alloys of aluminum with silicon) have high specific mechanical properties and are brittle materials that are hard to deform. Therefore, the search for ways to improve the structure of silumin considerably and enhance its plastic properties has always been and remains a relevant and important problem that is directly related to the challenge of expanding the field of application of these alloys in the aviation and automotive industries and other branches of industry. Large (up to 100 μm) crystals of primary silicon and other excess phases are formed in eutectic silumins under the conditions of conventional continuous ingot casting, and the eutectic contains laminar particles of eutectic silicon [1]. Rapid [2] and ultrafast [3] crystallization techniques are regarded as promising methods that allow one to reduce the size of silicon crystals and distribute them uniformly throughout an aluminum matrix. High-intensity pulsed electron beams are efficient tools for rapid heat treatment of the surfaces of metals and alloys [4]. If compared to widely applied laser technology, the electron-beam technology offers wider opportunities to monitor and adjust the amount of supplied energy and is characterized by a localized energy distribution in the surface layer of the material under treatment and a high efficiency. Ultrahigh rates (10^8–10^{10} K/s) of heating to the melting temperature and of subsequent cooling of a thin (10^{-7}–10^{-6} m) surface material layer, fairly short (10^{-6}–10^{-3}) times of exposure to high temperatures, and limiting temperature gradients (up to 10^7–10^8 K/m) that help cool the surface layer through heat extraction into the integrally cool bulk of the material at a rate of 10^4–10^9 K/s establish conditions for the formation of an amorphous nano- and submicrocrystalline structure in the surface layer [5]. It was demonstrated in a series of experiments [6–9] with stainless steels that the structure–phase transformations occurring in a modified surface layer under electron-beam treatment increase the fatigue life considerably.

The aim of the present study is to reveal the regularities of evolution of the structure and the fatigue life of eutectic silumin irradiated with a high-intensity pulsed electron beam of submillisecond duration and subjected subsequently to cyclic loading in the range of multiple-cycle fatigue to fracture.

2. MATERIALS AND METHODS

Eutectic silumin with the Al–10% Si composition served as the modified material. The surface silumin layer was subjected to pulsed melting under a high-intensity pulsed electron beam in a SOLO setup in the following modes: the electron energy was 18 keV, the energy density of the electron beam was 10–25 J/cm^2, the pulse duration was 50 or 150 μs, the number of pulses varied from 1 to 5, and the pulse repetition rate was 0.3 s^{-1}. Irradiation was performed in argon under a residual pressure of 0.02 Pa. These modes provided a rate of heating of the surface layer (with a thickness of up to 50 μm) to the melting temperature and melt quenching of up to 10^6 K/s. Just as in [6–9], fatigue tests were performed in the cyclical asymmetrical can-

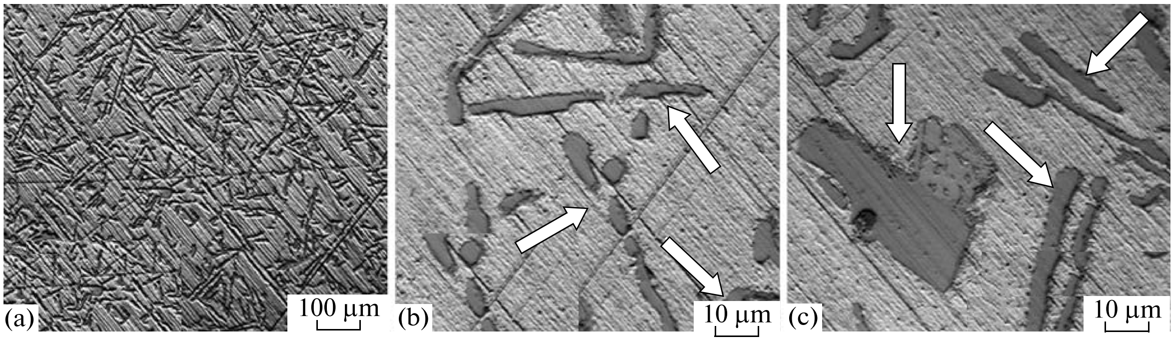

Fig. 1. Structure of eutectic silumin in its initial state. Arrows indicate silicon inclusions.

tilever bending arrangement at room temperature. The tested samples were shaped as parallelepipeds with a size of 8 × 14 × 145 mm. A crack was imitated by a cut in the form of a semicircle with a radius of 10 mm. The upper value of the load cycle (10 MPa) and the rate (15 Hz) were chosen experimentally for the studied material in such a way that the sample withstood a number of cycles corresponding in the range of multiple-cycle fatigue prior to fracture. The structure of the modified silumin layer was studied using metallography techniques and scanning electron microscopy (SEM).

3. RESULTS AND DISCUSSION

It was already noted that the structure of eutectic silumins is characterized by the presence of a large number of laminar primary silicon crystallites (Fig. 1). These crystallites are positioned chaotically or decorate the boundaries of alloy grains. The sizes of the lamina of the studied samples of silumin varied from several microns to a hundred microns in the section plane.

The results of fatigue tests of the silumin samples revealed a nonmonotonic dependence of the number of cycles to fracture on the mode of irradiation with a high-intensity pulsed electron beam (Fig. 2). The best result, which exceeded the fatigue life of the initial (unirradiated) silumin samples by a factor of more than 3.5, was demonstrated by those silumin samples that were irradiated with an electron beam having an energy of 20 J/cm^2 within 150 μs with 5 pulses at a repetition rate of 0.3 s^{-1}.

It is evident that the fatigue life of the silumin samples is defined primarily by the structure of their surface layer which was formed during electron-beam treatment. The samples that exhibited the best (in the mode of irradiation with 15 J/cm^2, 150 μs, and 1 pulse) and the worst (in the mode of irradiation with 20 J/cm^2, 150 μs, and 5 pulses) fatigue life were chosen for structural studies of the irradiated silumin surface.

Figures 3a and 3b show typical SEM images of the morphology of the surface silumin layer treated with a high-intensity pulsed electron beam in the mode with 15 J/cm^2, 150 μs, and 1 pulse. This silumin sample had the worst fatigue life. Analysis of the structural state of the modified surface showed that only aluminum was melted under irradiation. Rapid heat treatment under irradiation was followed by the emergence of multiple micropores and microcracks in the silicon laminae. The silicon laminae served as stress concentrators (i.e., sources of micro- and macrocracks in fatigue tests; see Fig. 3b). Taken together, the revealed specific features of the structure formed under irradiation in the indicated mode made it impossible to improve the fatigue life of the samples by irradiation.

Figures 3c–3e show the typical SEM images of the morphology of the surface silumin layer treated with a high-intensity pulsed electron beam in the mode with 20 J/cm^2, 150 μs, and 5 pulses. This silumin sample had the best fatigue life. A homogeneous grain-type (eutectic grain sizes varied from 30 to 50 μm) structure

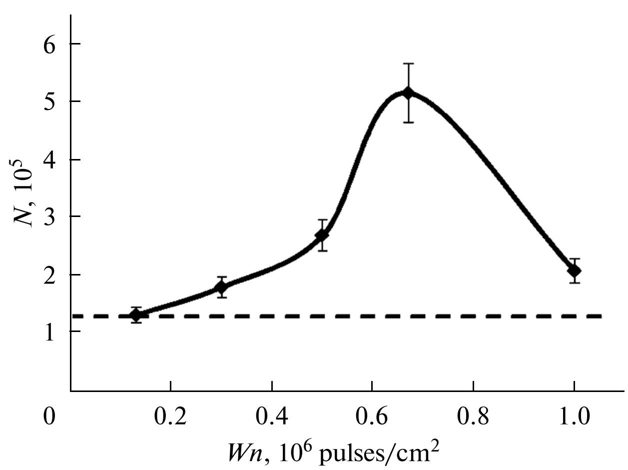

Fig. 2. Dependence of the number of cycles to fracture N on the total power density of the electron beam Wn (n is the number of pulses). The dashed line indicates the number of cycles to fracture for the initial samples.

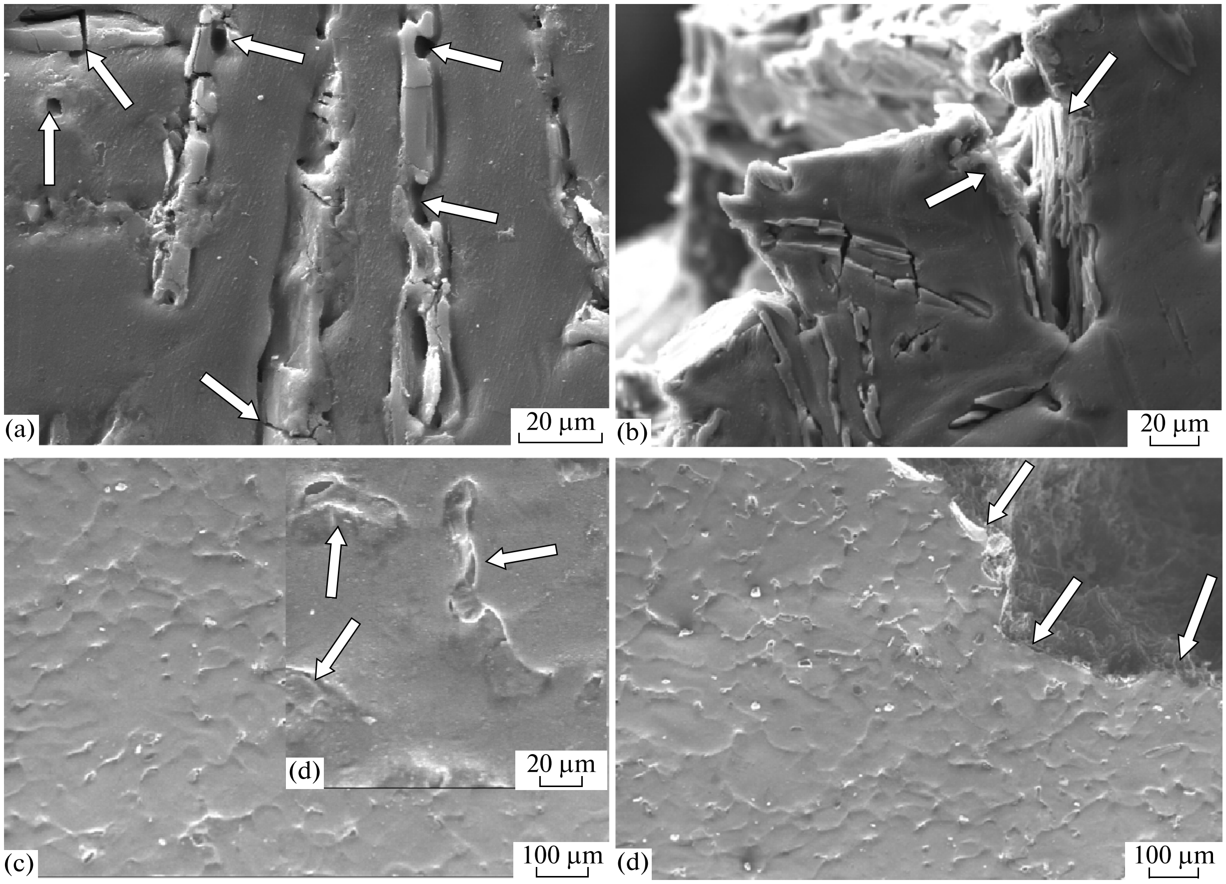

Fig. 3. SEM images of the surface of eutectic silumin samples treated with a high-intensity pulsed electron beam in the mode with (upper panels) $E = 15$ J/cm^2, $t = 150$ μs, and $n = 1$ pulse and (lower panels) $E = 20$ J/cm^2, $t = 150$ μs, and $n = 5$ pulses. Arrows indicate (a) micropores and microcracks, (b) the stress concentrator (silicon lamina) that induced macrocrack nucleation in the fatigue tests, (d) silicon particles, and (e) the fatigue fracture edge.

was formed on the sample surface. The grains were separated from each other by silicon laminae with their cross-section sizes being less than 20 μm (Fig. 3d). Stress concentrators that could serve as the sample-fracture origin were not found at the fracture edge. The concentrators that induced the sample fracture were probably located below the surface (apparently, at the boundary between the liquid and solid phases). Just as in [10], the presence of strong residual thermal stresses formed in the modified surface layer was one of the reasons for a reduction in the number of cycles to fracture at a total power density of the electron beam of 10^6 W pulses/cm^2.

4. CONCLUSIONS

The surfaces of samples of eutectic silumin were modified by a high-intensity pulsed electron beam. Fatigue tests revealed an irradiation mode that allowed us to increase the fatigue life of this material by a factor of 3.5. It was demonstrated that the dispersion and quasihomogeneous distribution of silicon crystals in the modified layer was the primary reason for this increase in the fatigue life of silumin. It was hypothesized that stress concentrators in the optimum irradiation mode were formed in the subsurface layer at the boundary between the liquid and solid phases.

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