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Electron beam modification of the structure and properties of silumins with various silicon concentrations

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Abstract. This work intended to analyse the structure and properties of hypoeutectic silumin treated by a pulsed electron beam. The study has shown that the silumin surface modified by a pulsed electron beam fractures due to the formation and propagation of microcracks along the boundaries of high-speed crystallization cells. In the untreated material (the concentration of silicon in the alloy is irrelevant) microcracks tend to originate and propagate along the phase boundaries between aluminum and silicon. The research has revealed that the plasticity of irradiated AK5M2 silumin is 1.6 higher and the strength is 1.1 lower than these characteristics of the untreated material; the irradiated AK10M2H silumin fractures at higher (by $\approx 30\%$) applied stress and higher (by 30%) plastic deformation than the untreated material.

1. Introduction

The progress in the field of generating pulsed and continuous electron beams [1-3], the development of relevant equipment and familiarization with it [4-6], the great number of studies within the materials science of metals and alloys, metal-ceramic and ceramic materials treated by electron beams have laid the foundation for the use of such energy sources in diverse industries, construction engineering and health care [5-17]. As demonstrated by a number of studies, a lot of research is being done in these domains, suggesting that at the moment the electron-beam treatment is a promising technology that has no alternative in some cases [17].

This work aims to explore the structure and properties of hypoeutectic silumin treated by a low-energy sub-millisecond pulsed electron beam.

2. Material and methods

For the purpose of research samples of as cast AK5M2 (Al-5Si-2Cu) and AK10M2H (Al-10Si-2Cu-1Ni) silumin were used. The irradiation was carried out using a laboratory unit “SOLO” equipped by a source of electrons based on a low-pressure pulsed arc discharge with the grid-stabilized boundary of cathode plasma and the open boundary of anode plasma [18]. The parameters of an electron beam were selected as follows: the energy of accelerated electrons – 17 keV, the energy density of an electron beam (30 and 50) J/cm², a pulse time – 200 μ s, a number of pulses – 3, the pulse frequency – 0.3 s⁻¹; the pressure of a residual gas (argon) in the processing chamber of the unit – 2×10^{-2} Pa. The tension tests of samples were performed using a testing machine “INSTRON 3386”.



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The distribution pattern of deformations in sub-surface layers of samples under tension was obtained by an optical measuring system VIC-3D [19]. The state of the fracture surface was explored with the help of scanning electron microscopy (“Philips SEM-515” and “LEO EVO 50”).

3. Results and discussion

The structure in the as cast AK5M2 and AK10M2H silumin consists of aluminum-based solid solution grains, Al-Si eutectics grains, inclusions of silicon and those of micron-size intermetallic compounds. The irradiation of the silumin surface by a pulsed electron beam results in the high-speed melting of an up to 90 μm deep surface layer. The subsequent high-speed crystallization brings about the formation of a cell-type structure [20]. A volume of cells is formed by the aluminum-based solid solution. The dimensions of cells vary from 200 nm to 600 nm. Along the cell boundaries there are lengthy thin layers of the second phase, which are enriched principally by silicon atoms. Needle-shaped inclusions of silicon and intermetallic compounds, which are typical for the as cast silumin structure, are not detected in the modified layer.

Mechanical tests were carried out on the untreated silumin and the material irradiated by an electron beam. The test results are given in figure 1. The stress-strain curves demonstrate that the brittle fracturing occurs in the material under the uniaxial tensile deformation in untreated and irradiated samples of hypoeutectic silumin. The hardening dominates the weakening and stress-strain curves stop in the hardening phase. The brittle fracturing in the material is also evidenced by an absent pre-fracturing phase on the stress-strain curves. The irradiation by a pulsed electron beam of the silumin surface brings about no significant transformations of stress-strain curves under the uniaxial tension; however, it changes numerical values of ultimate strength characteristics of silumin. The research has revealed that the plasticity of irradiated AK5M2 silumin is 1.6 higher and the strength is 1.1 lower than these characteristics of the untreated material (figure 1a); the irradiated AK10M2H silumin fractures at higher (by $\approx 30\%$) applied stress and higher (by 30%) plastic strain than the untreated material (figure 1b).

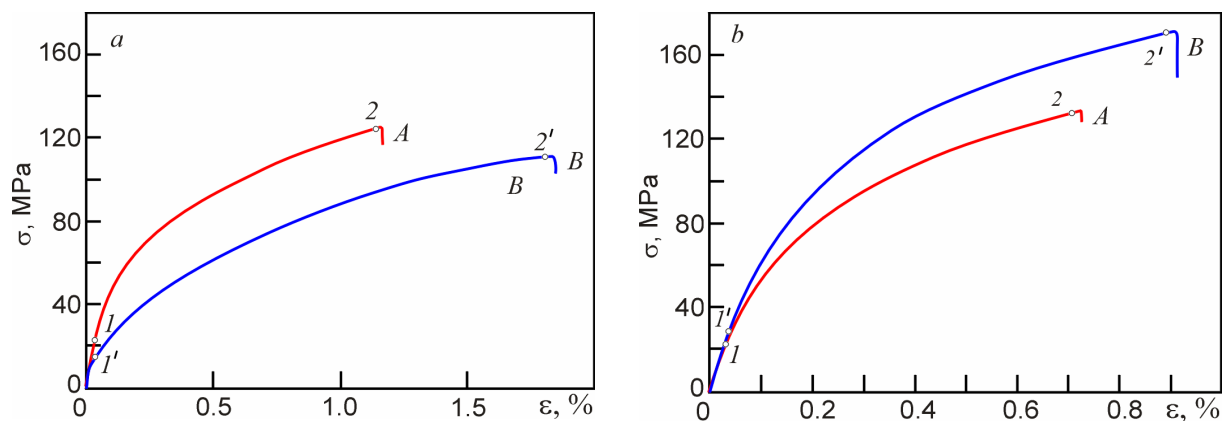


Figure 1. Stress-strain curves under the uniaxial tension of AK5M2 silumin samples (*a*: *A* – untreated AK5M2 silumin; *B* – irradiated by a pulsed electron beam: 30 J/cm², 200 μs , 3 pulses, 0.3 s⁻¹). AK10M2H (*b*: *A* – untreated AK10M2 silumin; *B* – irradiated by a pulsed electron beam: 50 J/cm², 200 μs , 3 pulses, 0.3 s⁻¹).

The speckle images of an elastic stage show that in irradiated and untreated samples of AK5M2 and AK10M2 silumin there are fragmented structures comprising local zones with different values of deformation in them provided that the deformation under the uniaxial tension is below 0.03 - 0.04%. The data presented in literature sources suggest that these local deformations are deformational or elastic-plastic regions. Moreover, these localization zones can contain even groups of grains.

It is apparent from the speckle images of lengthwise ε_{YY} relative deformations in untreated samples of AK5M2 and AK10M2 silumin under stress before fracturing that local zones of plastic deformation interfused with each other resulting in bigger zones with higher values of deformation. These local zones of deformation are located quasi-periodically in form of chains at an angle of about 45° . On the contrary, there are no such deformation patterns in the speckle images of irradiated samples. Interestingly, the plastic deformation in local zones of irradiated samples is much higher than in untreated samples under averaged deformations before fracturing.

The side edges of irradiated AK5M2 alloy samples represent sources of significant local deformations, while zones in the middle of irradiated AK10M2 alloy samples (figure 2, image 2' and figure 3, image 2') are also sources of considerable local strains.

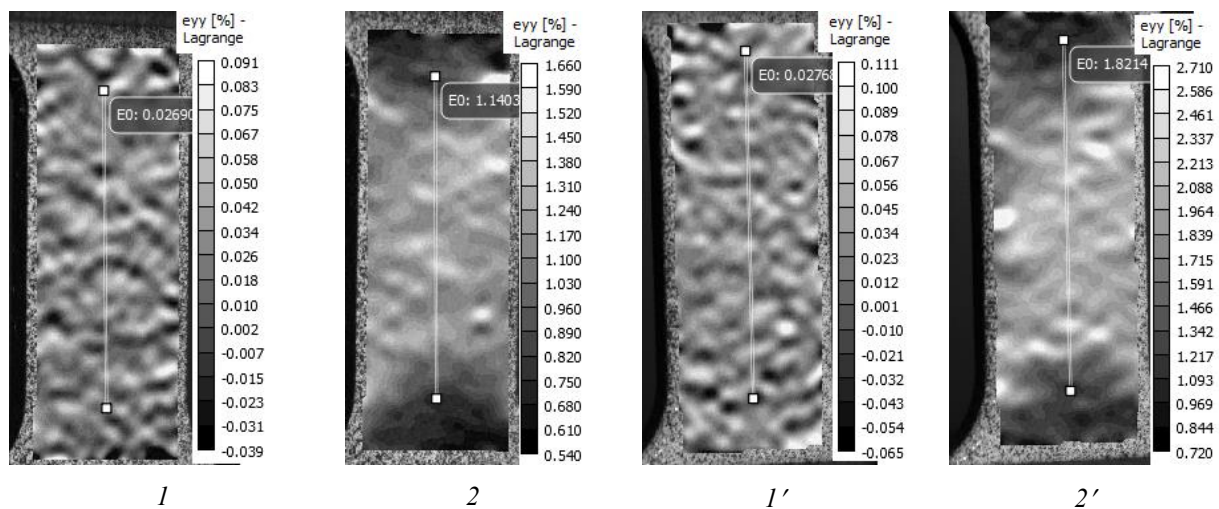


Figure 2. The distribution patterns of lengthwise ε_{YY} relative deformations on the surface of an untreated AK5M2 alloy sample under averaged deformations on the effective surface of a sample: 1) $\varepsilon_{YY} = 0.0269\%$; 2) $\varepsilon_{YY} = 1.14\%$; 1') $\varepsilon_{YY} = 0.0276\%$; 2') $\varepsilon_{XX} = 1.82\%$. These images correlate with points 1, 2 and 1', 2' on the stress-strain curves A and B, respectively (figure 1a).

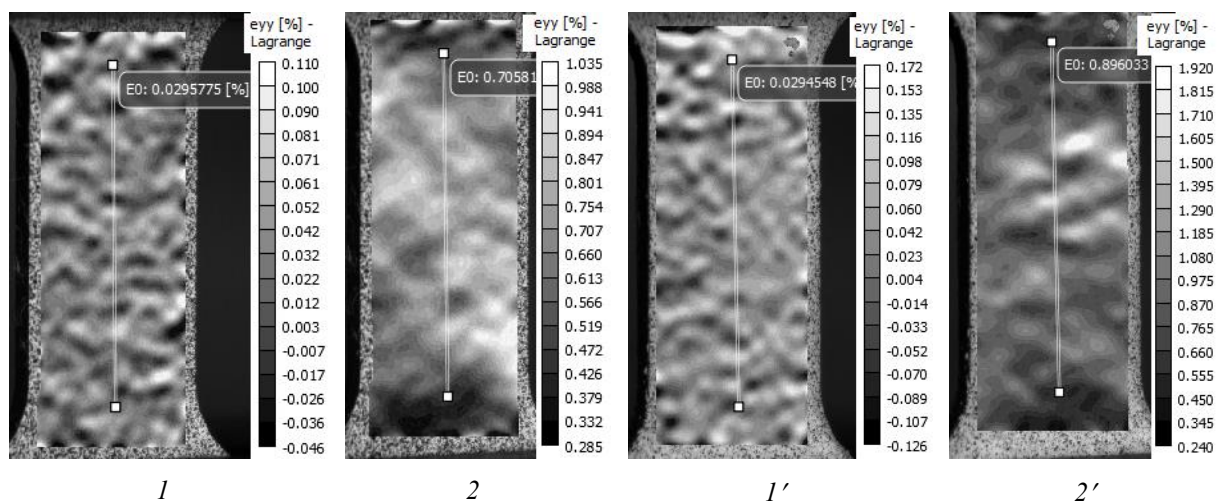


Figure 3. The distribution patterns of lengthwise ε_{YY} relative deformations on the surface of an irradiated AK10M2 alloy sample under averaged deformations on the effective surface of a sample: 1) $\varepsilon_{YY} = 0.029\%$; 2) $\varepsilon_{YY} = 0.706\%$; 1') $\varepsilon_{YY} = 0.029\%$; 2') $\varepsilon_{XX} = 0.89\%$. These images correlate with points 1, 2 and 1', 2' on the stress-strain curves A and B, respectively (figure 1b).

The fracture surface of silumin was explored. It has been found out that a modified layer in the AK5M2 silumin fractures along the boundaries of a columnar structure, which is formed when irradiating the material by a pulsed electron beam (figure 4a). The study on the fracture surface in the AK10M2H silumin revealed no columnar structure in the layer forming under the irradiation by a pulsed electron beam (figure 4b).

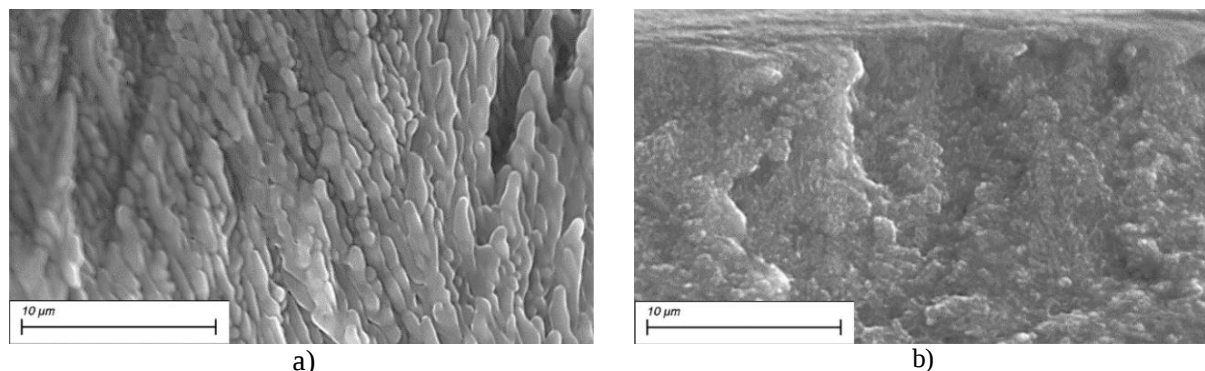


Figure 4. Electron-microscopic view of the fracture surface in AK5M2 (a) and AK10M2H (b) silumin under the uniaxial tension of plane proportional samples. Before stressing the effective surfaces of samples were irradiated from two sides by a pulsed electron beam: AK5M2 (30 J/cm^2 , $200 \mu\text{s}$, 3 pulses, 0.3 s^{-1}), AK10M2H (50 J/cm^2 , $200 \mu\text{s}$, 3 pulses, 0.3 s^{-1}).

4. Conclusion

The tensile testing of plane AK5M2 and AK10M2H silumin samples pre-irradiated by a pulsed electron beam was carried out. The tests revealed that the fracture in the silumin surface layer modified by a pulsed electron beam occurred due to the formation and propagation of microcracks along the boundaries of high-speed crystallization cells. The study detected the irradiation parameters which enhanced the plastic properties of silumin. An important outcome was that the plasticity of the irradiated AK5M2 silumin rose by 60% and the strength decreased by 10% in comparison with the untreated material; the irradiated AK10M2H silumin fractures at higher (by $\approx 30\%$) applied stress and higher (by 30%) plastic strain than the untreated silumin.

Acknowledgments

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