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Structure and properties of silumin irradiated with a pulse electron beam

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Abstract. The samples of silumin were irradiated with a pulsed electron beam. Studies of the structure and phase composition of the modified layer have been carried out. The formation of a submicro- nanocrystalline multiphase structure, formed as a result of high-speed crystallization of the surface layer, is revealed. Mechanical tensile tests were performed on samples of irradiated silumin, and an increase in the plasticity of the material by 1.2 times was revealed. It is shown that this effect is caused by stabilization of local macroregions with the compression deformation.

1. Introduction

Many cast aluminum alloys are based on the aluminum-silicon system and are called silumins. The aluminum-silicon double eutectic has a very coarse structure; silicon is precipitated in the form of plates, the size of which reaches hundreds of micrometers. Therefore, such alloys are subjected to modification, which consists in the fact that various additives are introduced into the melt before casting. For example, sodium formed as a result of an exchange reaction with a flux containing sodium fluoride. Silicon precipitates dramatically reduce in size under the influence of thousandths of a percent of sodium, and the strength and plasticity of the alloy increase. Coarse-needle eutectics and primary silicon precipitates lead to embrittlement, which increases with increasing silicon content in the alloy. The globular morphology of the eutectic is the best for mechanical properties. The best structure in the case of complete spheroidization of the silicon phase is achieved in eutectic silumins, because silicon inclusions are distributed most evenly [1]. Consequently, the development of methods allowing dispersing the structure of silumin is currently one of the promising directions for increasing the service characteristics of this material.

The method based on the use of pulsed electron beams of micro- and submillisecond duration of exposure is a promising modern method for modifying the structure and properties of metals and alloys, which allows forming multiphase nanostructured surface layers [2]. Ultra-high (up to 10^9 K/s) heating rates to melting temperatures and the subsequent cooling of a relatively thin (up to hundreds of micrometers) surface layer of the material, formation of limiting temperature gradients (10^7–10^8 K/m), providing cooling of the surface layer due to heat removal into the integrally cold volume of the material at a rate of (10^4–10^9) K/s, create conditions for formation of an amorphous, nano- and submicrocrystalline structure in the surface layer [2].

The aim of the paper is to discover and analyze the regularities of transformation of the structure and properties of silumin of the hypoeutectic composition, irradiated with a pulsed electron beam.

2. Material and research technique

Alloy AK5M2 (Al-(4-6) Si-1.3Fe-0.5Mn-0.5Ni-0.2Ti-2.3Cu-0.8Mg-1.5Zn, wt.%) was used as the material for the study. The irradiation of silumin samples with an intense pulsed electron beam was carried out on a SOLO installation (Institute of High Current Electronics SB RAS) [3]. The electron beam parameters were as follows: accelerated electron energy was 17 keV, electron beam energy density was (30, 50) J/cm^2, pulse duration was (50 and 200) μs, number of pulses was 3, pulse repetition rate was 0.3 s^{-1}; residual gas pressure (argon) in the working chamber of the unit was 2*10^{-2} Pa. The elemental and phase composition, the state of the defect substructure and the fracture surface were studied by scanning electron microscopy (the device Philips SEM-515 with a microanalyzer EDAX ECON IV) and transmission electron diffraction microscopy (the device JEM 2100F, JEOL). Mechanical tests of silumin were carried out by uniaxial tension of flat proportional samples on an INSTRON 3386 testing machine at a constant speed of 1.25 mm/min. The distribution of deformations in the near-surface layers of the sample under tension was recorded using an optical measuring system VIC-3D [4]. This system allows obtaining distribution patterns of deformation fields based on correlation of digital stereoscopic images. This allows obtaining data on the movement of microvolumes in three-dimensional space are obtained. Prior to deformation, speckle structures on the surface of the samples were formed by applying contrasting finely dispersed colors with white and black matte aerosol paints [5]. This allowed obtaining displacement fields in the process of deformation, which are projections of displacements of local sections of the sample surface along the OX axis – “transverse deformation” and along the OY axis – “longitudinal deformation”, which are then converted into relative deformations (ε_{xx} is along the X axis, ε_{yy} is along the Y-axis, ε_{xy} is the shear deformation). The deformation pattern of the surface was obtained by combining microregional changes.

3. Results and discussion

Using methods of transmission electron diffraction microscopy, it has been established that irradiation of silumin with a pulsed electron beam leads to formation of a submicro-nanocrystalline columnar structure as a result of high-speed crystallization of the molten surface layer (Figure 1, a). It has been found that the volume of the pillars was formed by a solid solution based on aluminum. The columns are separated by interlayers enriched with silicon, copper, and iron atoms (Figure 1, b-d). The transverse dimensions of the columns vary within 150-800 nm and increase with increasing energy density of the electron beam. The transverse dimensions of the interlayers dividing the columns vary within the range of up to 100 nm.

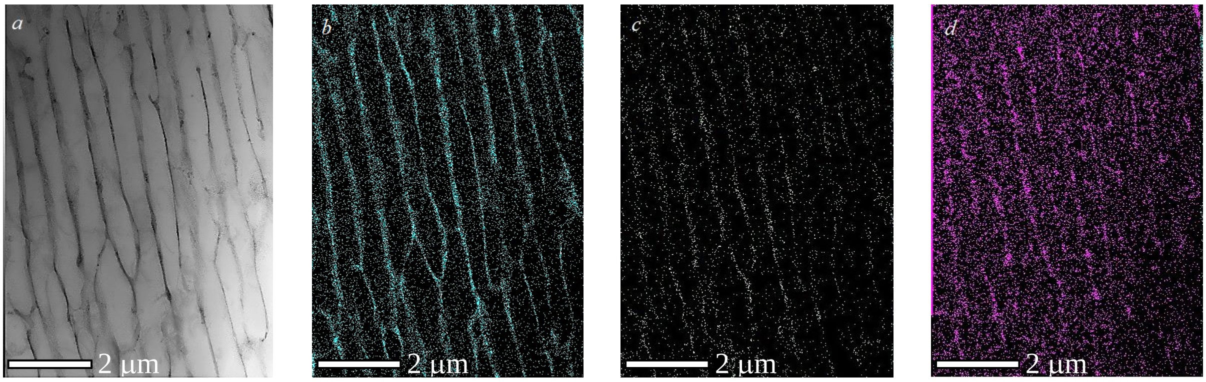

Figure 1. Electron microscopic image of the structure of AK5M2 silumin irradiated with a pulsed electron beam (50 J/cm^2, 200 μs, 3 pulses, 0.3 s^{-1}), obtained using the STEM method (*a*); b-d are images of the given foil area obtained in characteristic X-ray radiation of silicon (b), iron (c), and copper (d) atoms.

The results of the studies of mechanical properties are shown in Figure 2. Given in Figure 2 *a*, the deformation curves in the coordinates σ – ε show that brittle fracture of the material occurs during uniaxial deformation by tension of the initial and irradiated sample. It is seen that hardening prevails over softening and the deformation curves break off at the hardening stage. The brittle nature of material destruction is also evidenced by the absence of the pre-fracture stage on the deformation curves. Irradiation of the silumin surface with a pulsed electron beam does not lead to noticeable changes in the shape of the deformation curves under uniaxial tension. Mechanical tests of silumin, performed by uniaxial tension of flat proportional samples, have revealed a slight increase in the plasticity of the irradiated material by a factor of 1.2 (Figure 2).

Deformation curves were plotted in coordinates σ–ε^n with n values from 0.1 to 0.5 to select straight sections on the deformation curve. The analysis of the plotted deformation curves in the coordinates σ–ε^n with different values of n has allowed finding that the most distinctly rectilinear sections on the deformation curves are distinguished on the graphs plotted in the coordinates σ–$\varepsilon^{0.33}$ (Figure 2 *b*). As a result, three stages can be distinguished on the deformation curves in the coordinates σ–$\varepsilon^{0.33}$. The first stage is transitional (π). This stage is followed by stages II and III, characterized by different values of the strain hardening coefficient Θ. Formation of stages on curves σ–ε reflects a change in the mechanisms of strain hardening during the transition from one stage to another, and is confirmed by a change in the distribution of strain fields in speckle patterns (Figure 3 and Figure 4). It can be seen that the transition from the microelastoplastic transitional stage to stage I is accompanied by enlargement of local foci of the plastic deformation.

In [6] it was shown that these local small deformation regions can be represented as deformation or elastoplastic domains at the mesoscale. These localization regions are distributed in a quasiperiodic manner on the surface of the samples (Figure 3 and 4, speckle patterns 1 and 1′). Then, the elastoplastic domains merge into larger regions as the external applied stresses increases. As a result, these larger regions of deformation localization already include whole groups of grains at the macrolevel.

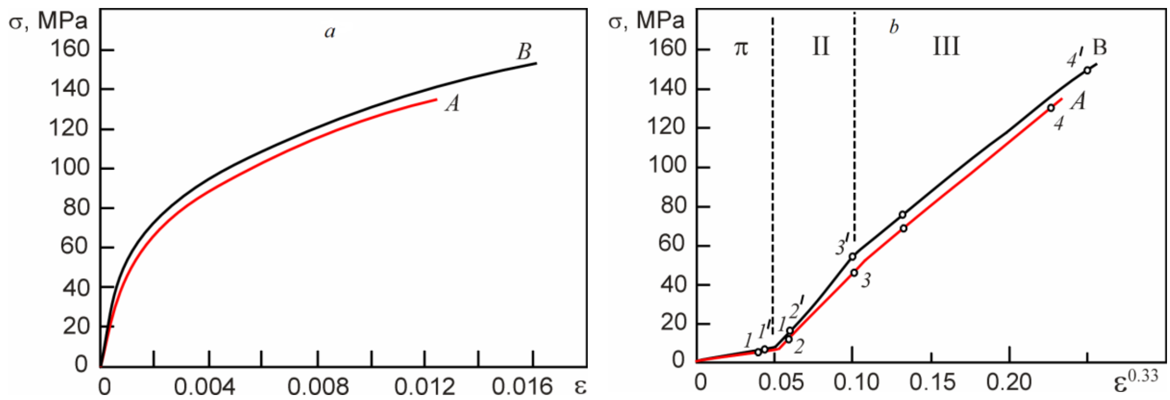

Figure 2. Deformation curves of non-irradiated (curve A) and irradiated (curve B) samples plotted in coordinates σ–ε (*a*) and σ–$\varepsilon^{0.33}$ (*b*). Dashed lines indicate areas with different stages of strain hardening. Points 1 – 5 and 1′ – 5′ on the deformation curves show the states for which the speckle patterns are shown in Fig. 3 and 4 respectively

Based on the analysis of speckle patterns of the distributions of vertical ε_{YY} relative deformations on the surface of the irradiated sample, it has been found that the maximum value of deformation in local foci of plastic deformation at the same average deformations over the entire working field is higher than the maximum value of deformation in local foci of plastic deformation in unirradiated samples.

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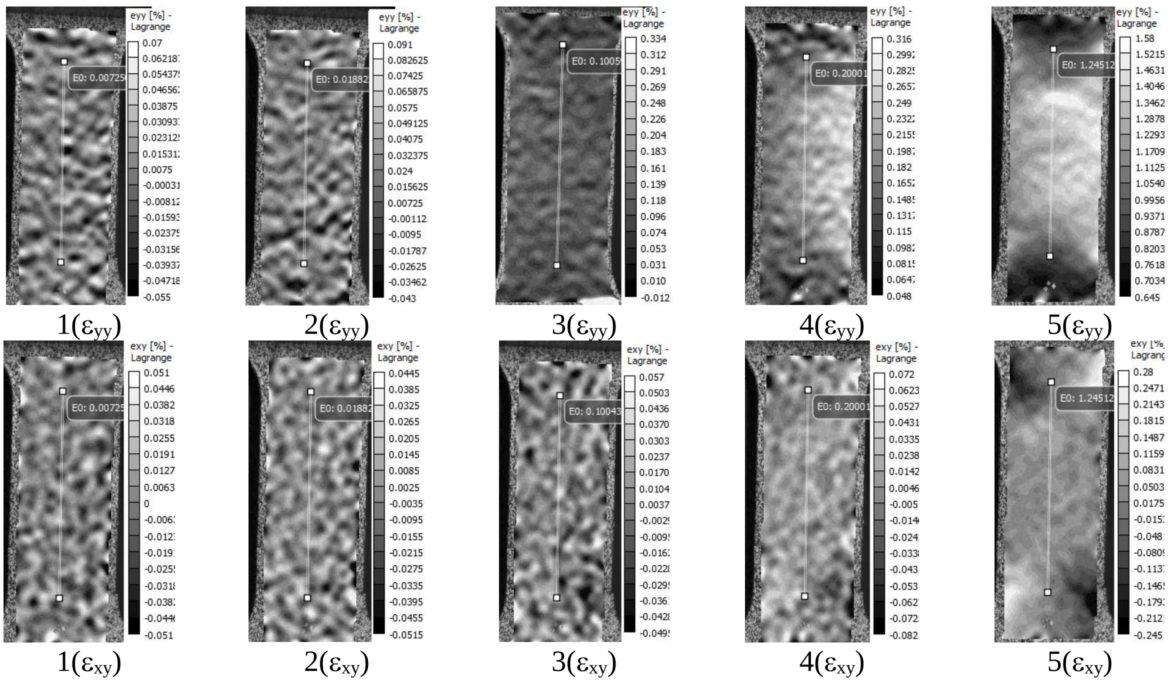

Figure 3. Speckle patterns of the distributions of vertical ε_{YY} and shear ε_{XY} relative deformations on the surface of the unirradiated sample under uniaxial tension at different averaged deformations over the working field of the samples: 1(ε_{yy}), 1(ε_{xy}) is ε_{YY}=0.007%; 2(ε_{yy}), 2(ε_{xy}) is ε_{YY}=0.018%; 3(ε_{yy}), 3(ε_{xy}) is ε_{YY}=0.100%; 4(ε_{yy}), 4(ε_{xy}) is ε_{YY}=0.200 %%; 5(ε_{yy}), 5(ε_{xy}) is ε_{YY}=1.245%. Speckle pattern numbers correspond to points 1 – 5 on the deformation curve A in Figure 2b

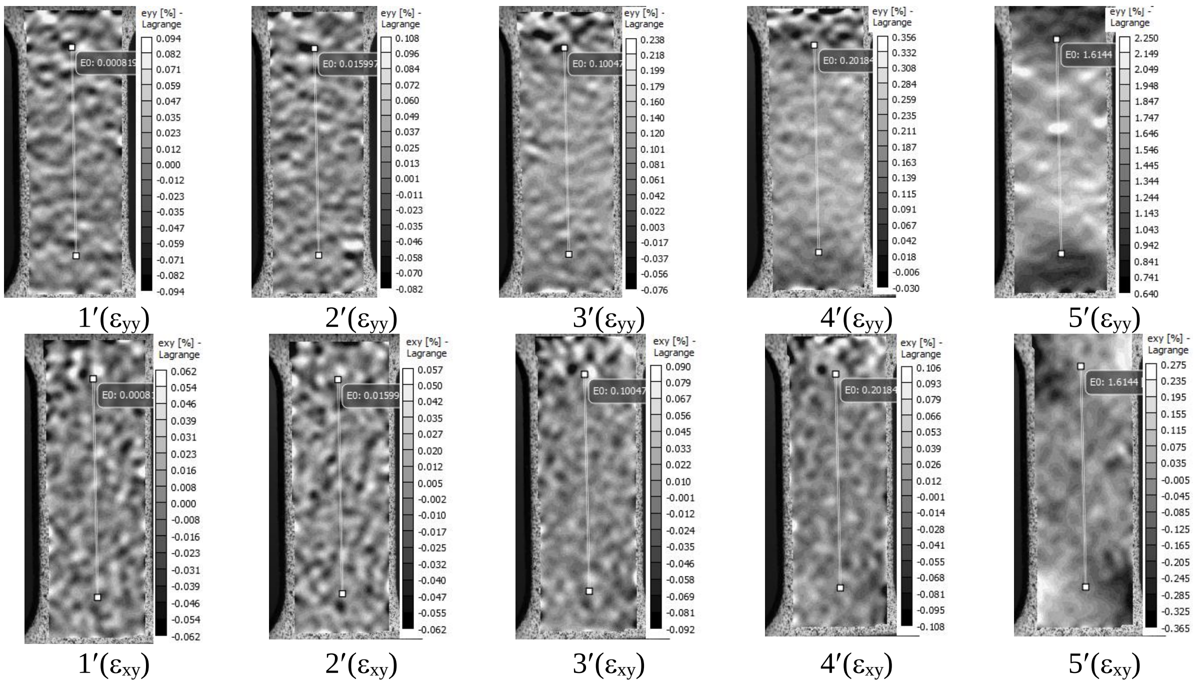

Figure 4. Speckle patterns of the distributions of vertical ε_{YY} relative and shear ε_{XY} deformations on the surface of the irradiated sample (50 J/m^2, 50 μs, 3 pulses) under uniaxial tension at different averaged deformations over the working field of the samples: 1′ (ε_{yy}), 1′(ε_{xy}) is ε_{YY}=0.0008%; 2′(ε_{yy}), 2′(ε_{xy}) is ε_{YY}=0.016%; 3′(ε_{yy}), 3′(ε_{xy}) is ε_{YY}=0.100%; 4′(ε_{yy}), 4′(ε_{xy}) is ε_{YY}=0.202%; 5′(ε_{yy}), 5′(ε_{xy}) is ε_{YY}=1.614%. Speckle pattern numbers correspond to points 1′ – 5′ on the deformation curve B in Figure 2b

4. Conclusion

The irradiation of hypoeutectic silumin with an intense pulsed electron beam has been carried out. Formation of a multiphase submicro-nanocrystalline columnar structure in the surface layer has been revealed. It has been found that the volume of the pillars was formed by a solid solution based on aluminum; the columns are separated by interlayers enriched mainly in silicon, copper, and iron atoms. Mechanical tests of silumin were carried out by uniaxial tension of flat proportional samples. An analysis of the displacement fields of microregions of the material at various stages of sample deformation has been carried out by studying the speckle patterns formed before deformation. It has been shown that formation of a submicro-nanosized columnar structure contributes to stabilization of local macroregions with compression deformation. This is accompanied by an increase in the plasticity of the irradiated material by a factor of 1.2 relative to the unirradiated state.

Acknowledgments

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