Deformation of silumin subjected to a pulsed electron beam treatment

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Abstract. Using a virtual extensometer, it was found that irradiation with a pulsed electron beam (18 keV, 15 J/cm², 200 μs, 3 pulses, 0.3 s⁻¹) leads to an increase in the strength properties of the hypoeutectic silumin samples by 30%. The deformation curves in the coordinates «σ-ε» and «σ-√ε» did not reveal inflection points that characterize the stages of deformation transformation of the material. This indicates that the transitions from stage to stage in this class of materials are blurred.

1. Introduction

Almost all wear, corrosion, growth of fatigue cracks processes etc., leading to the failure of parts and mechanisms, begin from the surface and are determined by the properties of a relatively thin surface layer [1]. Consequently, in some cases, to increase the product service life, it is sufficient to modify its surface layer. Currently, methods based on the use of concentrated energy flows, including combined electron-ion-plasma methods are promising, demonstrating the high efficiency of products surface modification [2].

The aim of this work is to establish and analyze the regularities of plastic deformation of silumin irradiated by an intense pulsed electron beam and subjected to tensile deformation.

2. Materials and method

Silumin of AK10M2N brand, widely used in mechanical engineering, aerospace industry, shipbuilding, instrument making, medicine, etc., was used as an object of modification [3]. Modification of silumin specimens was carried out on a SOLO setup [4]. Mechanical tests of silumin specimens were carried out by stretching proportional flat specimens with heads in accordance with the International Standard “ISO 6892-84. Metals. Methods of tension test”, that regulates the dimensions of the specimens used for tensile tests [5]. The electron beam was oriented along the normal to the specimen plane during irradiation. The surface of the samples was irradiated from both sides with an electron beam with the parameters 18 keV, 15 J/cm², 200 μs, 3 pulses, 0.3 s⁻¹.

The study of the processes occurred during silumin deformation was carried out using the contactless method of digital image correlation (DIC) [6]. Using this method, with a virtual extensometer, the
deformation curves were obtained by uniaxial tension of flat specimens. The use of the digital image correlation method made it possible to analyze the images of the investigated surface of a solid specimen to obtain qualitative and quantitative characteristics of the deformations fields, displacements, and velocities. The deformation pattern of a surface is obtained by combining changes in sub-regions. Speckle structures are artificially applied to the surface of solid specimen to form a contrasting pattern. The Vic3D digital optical system uses the principle of digital stereoscopic images correlation, that makes it possible to obtain data on the movement of the sample surface in space. Shooting from two digital cameras allows obtaining a stereoscopic image of the specimen surface. Analyzing them, the movement of points on the specimen surface in three axes (in space) is determined. Using the digital image correlation method implemented in the Vic3D digital optical system, the geometric parameters of the surface (X, Y, Z coordinates for each analyzed point) are calculated, as well as displacement at each point (U, V and W, indicating displacements along the X axes, Y and Z, respectively), relative deformations (\(\varepsilon_{xx}\) - along the X axis, \(\varepsilon_{yy}\) - along the Y axis, \(\varepsilon_{xy}\) - shear deformations), the rate of change in displacement and deformations, surface curvature.

3. Results and discussion

It was found that irradiation of silumin with a pulsed electron beam in the melting mode of a relatively thin (up to 20 \(\mu\)m) surface layer and subsequent high-speed crystallization lead to the formation of a cellular crystallization structure (solid solution based on an aluminum crystal lattice) with dimensions (200-250) nm. Nanosized (30-50 nm) particles of silicon and intermetallic compounds are located in the volume and along the boundaries of the cells [7].

The figure 1 shows the deformation curves in coordinates \(\sigma\) from \(\varepsilon\) and \(\sigma\) from \(\sqrt{\varepsilon}\) for specimens before irradiation and after irradiation with an intense pulsed electron beam. It is seen that irradiation of silumin with a pulsed electron beam makes it possible to increase the plasticity of the specimen.

![Deformation Curves](image)

**Figure 1.** Tensile strain curves of silumin specimens in \(\sigma\) coordinates from \(\varepsilon\) (a) and from \(\sqrt{\varepsilon}\) (b) before irradiation (I) and after irradiation with an intense pulsed electron beam (II).

The staging of deformation curves by processing the hardening curves in coordinates \(\sigma-\varepsilon\) is the standard approach. The inflection points on the deformation curves can be used to judge the structural changes occurring in the alloys. The presence of inflection points on the deformation curves in the \(\sigma-\varepsilon\) coordinates indicates structural changes during deformation. There are no characteristic inflection points on the deformation curves in the coordinates \(\sigma-\varepsilon\) and \(\sigma-\sqrt{\varepsilon}\) (figure 1), in the studied silumin. Their absence indicates that the transitions from stage to stage in this class of materials are blurred.

On the other hand, the non-monotonic nature of the change in the given deformation curves in the coordinates \(\sigma-\varepsilon\) and \(\sigma-\sqrt{\varepsilon}\) reflects the temporary inhomogeneity of the process of plastic deformation of the alloy. This phenomenon is accompanied by localization of deformation processes at various scale and structural levels [8] and is confirmed by the deformation field distributions patterns on the surface of the samples under study depending on the deformation degree (figures 2-3). The figure 2 shows the pictures of the deformation fields distributions for points 1-5 indicated in the diagrams in the figure 1. Macrovolumes located in a chaotic manner are observed, in which plastic deformation of the
material occurs. At the initial stage, the centers of local deformation are formed mainly on the lateral sides of the sample. With an increase in the applied stress, they come into contact with the formation of the so-called deformation channels located at an angle of 45 degrees to the lateral surface of the specimen [9].

Figure 2. Pictures of longitudinal distributions $\varepsilon_{YY}$ relative deformations on the surface of an unirradiated silumin specimen. Patterns 1 - 5 correspond to points 1 - 5 on the deformation curve I in figure 1.

Figure 3. Pictures of longitudinal distributions $\varepsilon_{YY}$ relative deformations on the silumin specimen surface irradiated with a pulsed electron beam. Patterns 1' - 5' correspond to points 1'-5' on a deformation curve II in figure 1.
The deformation fields distribution patterns during stretching of the specimen irradiated with an electron beam (figure 3) are similar to the deformation fields distributions patterns on the original sample (figure 2). As in the case of deformation of unirradiated silumin, stretching of the irradiated specimen is accompanied by the formation of regions with high values of longitudinal deformations $\varepsilon_{YY}$ at the last stage of the deformation curve, localized on the lateral face of the specimen. The difference is the formation of compression zones on the surface between tensile local deformation zones (figure 3).

Further study of the features of the effect of irradiation on the mechanical properties of silumin specimens was carried out by plotting diagrams in coordinates $\sigma - \varepsilon_{YY}$ and $\sigma - \sqrt{\varepsilon_{YY}}$. Here $\varepsilon_{YY}^{\max}$ the maximum values of deformations inside the centers of plastic deformation in the longitudinal direction; $\varepsilon_{YY}^{\min}$ minimum values of deformations in the longitudinal direction in the accommodation zones (figure 4).

It can be seen that with an increase in the external applied tensile stress $\varepsilon_{YY}^{\max}$, they increase in a non-linear manner in the initial and irradiated samples (figure 4, a). In irradiated samples, the increase $\varepsilon_{YY}^{\max}$ occurs more intensively with an increase in the applied tensile stress. In zones with minimal deformations values in the longitudinal direction, an oscillating character of the change in deformations from the applied stress is observed with a general tendency towards an increase in numerical values (figure 4, b). This indicates that accommodative processes occur in the main zones with minimal deformation values.

![Figure 4](image-url)

**Figure 4.** Dependences of the maximum values of deformations along the longitudinal direction in the area of the centers of plastic deformation $\varepsilon_{YY}^{\max}$ (a) and in the area of minimum values of deformations $\varepsilon_{YY}^{\min}$ (b). 1 – original sample; 2 – sample irradiated with a pulsed electron beam.

### 4. Conclusion

Using a virtual extensometer, it was found that irradiation with a pulsed electron beam (18 keV, 15 J/cm$^2$, 200 $\mu$s, 3 pulses, 0.3 s$^{-1}$) leads to an increase in the strength properties of the hypoeutectic silumin samples by 30%. The deformation curves in the coordinates $\sigma - \varepsilon$ and $\sigma - \sqrt{\varepsilon}$ did not reveal inflection points that characterize the stages of deformation transformation of the material. This indicates that the transitions from stage to stage in this class of materials are blurred. The non-monotonic nature of the change in the deformation curves in the coordinates $\sigma - \varepsilon$ and $\sigma - \sqrt{\varepsilon}$ is established, that reflects the temporal inhomogeneity of the process of inelastic deformation of the alloy. The manifestation of this process correlates well with the evolution of deformation fields on the surface of the samples. Moreover, this phenomenon is most clearly observed on irradiated samples.

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