Silumin strengthening mechanisms

E A Petrikova and Yu F Ivanov
Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk 634055, Russia
E-mail: elizmarkova@yahoo.com

Abstract. With the aim of developing a new class of wear-resistant nanocomposites, eutectic silumin was exposed to micro- and submillisecond intense electron beam irradiation with surface melting. Due to such modification, which provides high-rate solidification, a submicro-nanocrystalline structure with enhanced strength was formed in a silumin surface layer of up to 500 µm thick. The elemental composition and the defect structure of the irradiated material were analyzed by scanning and transmission electron microscopy, and its phase and lattice states were studied by X-ray diffraction analysis.

1. Introduction
The service properties of metals and alloys can be increased by forming their submicro- and nano-sized multiphase structure [1-4], and among the modern methods which can provide such modification is irradiation with micro- and submillisecond low-energy (up to 30 keV) intense pulsed electron beams.

Eutectic alloys contain 9-13% of Si, and their structure comprises dendrites of α-solid solution and a small amount of primary Si crystals [5]. The lower bound of silicon serves to provide desired casting properties, and the upper level to provide minimum plasticity, as the Si phase is brittle. The presence of coarse needle-like eutectics and primary Si inclusions leads to embrittlement which increases with Si content, and their refinement with spheroidization can increase the strength of such materials by 30-40% and their elongation by a factor of 2-3. Thus, developing methods for structural dispersion of silumin is a promising way toward its better service properties.

Electron beam irradiation in optimum modes allows one to form a nanostructured surface layer in silumin and to greatly improve its physicochemical and strength properties, which is unattainable by conventional surface treatments [1-8].

Here we analyze the strengthening of eutectic silumin irradiated with an intense electron beam from quantitative estimates of its structural parameters.

2. Test material and research techniques
The test material was a commercial antifriction eutectic alloy based on aluminum (silumin) which contained 12.49 % Si, 2.36 % Mg, 0.6 % Cu, 0.35 % Ni, 0.3 % Fe, and balance Al at%. The material was shaped into cylinders of diameter 10 mm and thickness 5 mm and was irradiated with an intense pulsed electron beam.
on a SOLO setup at a beam energy density of 20 J/cm$^2$, pulse duration of 150 µm, and gas (Ar) pressure of 0.02 Pa. The number of pulses was $N=1-50$.

The surface morphology and the elemental composition of silumin surface layers were studied by scanning electron microscopy and energy dispersive X-ray analysis (Philips SEM515 microscope and EDAX ECON IV microanalyzer). The phase composition was studied by X-ray diffraction analysis (XRD 6000 diffractometer). The defect substructure of the material before and after electron beam irradiation was examined by thin-foil transmission electron microscopy (JEM 2100F microscope). The material was tested for tension and bend (Instron 3369 machine), and its surface roughness was analyzed (MNP-1 profilometer).

### 3. Results

When irradiated in the modes used, the silumin undergoes surface melting, dissolution of Si particles and intermetallic compounds, mixing of elements in the melt via convection, and high-rate solidification (quenching) with the formation of a submicro-nanocrystalline multiphase structure composed of dendrite cells (figure 1). The surface roughness of the mechanically polished material after irradiation varies 0.7 to 1.5 µm. The least roughness is observed after irradiation at $N=10$ pulses.

![Figure 1. Structure of cast eutectic silumin before (a) and after electron beam radiation (b, c).](image)

Our mechanical tests show that after irradiation in optimum modes (20 J/cm$^2$, 150 µs, 1-3 pulses, 0.3 Hz), the surface microhardness of the material through a depth of up to 50 µm increases ~1.5 times compared to its bulk. The silumin structure is repeatedly dispersed with the dissolution of large Si particles and intermetallic phases, and this increases the ultimate bending and tensile strength of the material ~1.2 and ~1.4 times, respectively, and its bending and tensile plasticity ~1.2 and ~1.8 times, respectively (figure 2).

The yield strength of the initial silumin is 58-60 MPa, and after irradiation, it is 90-95 MPa (figure 2b). The main factors responsible for the strength properties of silumins include the presence of grain boundaries, solid solution and second phase particles, and dislocation substructure. For assessing the strengthening of the alloy under electron beam irradiation, we used the constants [9-13]: $b=0.286$ nm, $G_{Al}=26$ GPa, $M=3.06$, $\alpha=0.3$, $k_s=1.4$ MPa-mm$^{1/2}$, $G_{Si}=63$ GPa, $K=30$, $K_{Mg}=14.9$ MPa, $K_{Cu}=66.2$ MPa, $K_{Si}=22$ MPa, $C_{Mg}=0.6$, $C_{Si}=1.1$, and $\nu=0.34$.

The yield strength $\sigma$ is related to the scalar dislocation density as follows [14–16]:

$$\sigma\rho=\chi_0MGAlb\sqrt{\rho}\sigma,$$  

(1)
where \( b \) is the Burgers vector of aluminum, \( \rho \) is the average (scalar) dislocation density, \( G_{\text{Al}} \) is the shear modulus of aluminum, \( M \) is the Taylor factor, \( \alpha \) is a constant, and \( \chi = 0.85 \) is the coefficient accounting for dislocation structure heterogeneity [17].

\[
\sigma_b = \sigma_0 + k y / D_g, \tag{2}
\]

where \( \sigma_0 \) is the lattice friction stress of a material (Peierls stress for pure metals), \( D_g \) is the grain size in \( \text{mm} \), and \( k_y \) is the Hall–Petch coefficient dependent on the purity of a material, hardening of boundaries by second phase particles, and boundary structure [14, 20, 21]. Single-crystal aluminum, like other fcc metals, features a very low lattice resistance to dislocation motion. The Peierls–Nabarro stress is \( \tau_0 < 10^{-5} G \), where \( G \) is the shear modulus [22]. Then, for aluminum we have \( \tau_0 < 0.25 \text{ MPa} \), and the so small value can be further ignored. In the best irradiation mode, the contribution to the yield strength by eutectic grain refinement is \( \approx 14 \text{ MPa} \). The size of pure Al grains changes slightly, and the contribution of such refinement is small, measuring \( \approx 10 \text{ MPa} \) in all irradiation modes.

The chief cause of strengthening is the formation of barriers to dislocation motion. Such barriers are particles not intersected by dislocations (incoherent). They cause curvature in dislocation lines, and their contribution to the yield strength can be estimated as follows [23, 24]:

\[
\sigma_p = M m \sigma_m b / \left( 2 \pi (\lambda - D) \right)^{1/2} \ln \left( \frac{\lambda - D}{4b} \right), \tag{3}
\]

where \( D \) is the average particle size, \( m \) is the orientation factor equal to 3.03 for fcc materials, \( \Phi = (1 - v)^{-1} \) for edge dislocations, and \( M \) is the parameter accounting for particle distribution nonuniformity in a matrix and equal to 0.81-0.85 [25].

**Figure 2.** Stress-strain curves of silumin in bending (a) and tension (b) after irradiation with 3 pulses at 20 J/cm\(^2\), 150 \( \mu \)s and 0.3 Hz.
The Si particles present in silumin are incoherent. Their contribution to the yield strength varies little with increasing the number of pulses: from 57 to 62 MPa.

The substitutional solid solution strengthening of a material depends on the difference between the sizes of solvent and solute atoms and on the disturbance of its electronic structure. In the silumin studied, the Al solid solution can contain Mg and Cu; that is, the contribution to the yield strength is determined as [12, 14]:

$$\sigma_{ss} = K_{Si}C_{Si} + K_{Mg}C_{Mg} + K_{Cu}C_{Cu}, \quad (4)$$

According to estimates, its maximum value is $\sigma_{ss} = 3.8$ MPa.

As has been shown [26-28], best suitable for describing the strengthening of eutectic alloys is a model based on the rule of mixtures in which the mixture components are Al and AlSi grains, and the yield strength can thus be estimated as:

$$\sigma_{0.2} = (1 - f_{eu})(\sigma_{ss} + \sigma_{gb}) + f_{eu}(\sigma_{ss} + \sigma_{p} + \sigma_{r}), \quad (5)$$

where $f_{eu}$ is the eutectic volume fraction, and $\sigma$ is the strengthening by solid solutions $\sigma_{ss}$ (equation (1)), dislocations $\sigma_{r}$ (equation (2)), grain boundaries $\sigma_{gb}$ (equation (3)), and second phase particles $\sigma_{p}$ (equation (4)).

In the silumin under study, the eutectic volume fraction is 89%, and the contribution to its yield strength from the values estimated above is $\sigma_{0.2} = 136$ MPa after irradiation with one pulse at 20 J/cm$^2$, 150 µs.

For the initial silumin, $\sigma_{0.2} = 50$ MPa because the contribution from its dislocation substructure and second phase particles is rather small. These results and the values in figure 2 show a good qualitative and quantitative agreement suggesting that the estimates are valid.

4. Conclusion
A modification of the surface layer of the silumin of the AK12M2MgN with an intense pulsed electron beam has been carried out. X-ray structural and electron-microscopic studies of elemental and phase composition, the state of the defective substructure of the modified layer were performed. The results of a quantitative analysis of the structural-phase state of the material were used to estimate the magnitude of the hardening mechanisms at the yield point of silumin irradiated by an intense pulsed electron beam. It is shown that the yield strength of the material is contributed mostly by second phase particles and somewhat less by its dislocation substructure.

Acknowledgments
The work was supported by the Russian Science Foundation (project No. 14-29-00091).

References
[1] Laskovnev A P et al. 2013 Modification of the structure and properties of eutectic silumin using electron-ion-plasma treatment (Minsk: Belorus. Nauka) p 287
[2] Koval N N et al. 2016 Electron-ion-plasma surface modification of non-ferrous metals and alloys (Tomsk: Izd. Nauch. Tekh. Lit.)
[3] Ivanov Yu F et al 2017 Fiz. Khim. Obr. Mater. 3 38
[4] Koval N N and Ivanov Yu F 2008 Izv. Vyssh. Uchebn. Zaved. Fiz. 51 60
[5] Belov N A 2008 Phase composition and structure of silumines (M.: MISIS) p. 282
[6] Lotkov A I et al 2008 Surface nanoengineering. Formation of nonequilibrium states by electron-ion-plasma technologies (Novosibirsk: SB RAS)
[7] Rotshtein V, Ivanov Yu and Markov A 2006 Materials surface processing by directed energy techniques (Paris: Elsevier, Ed. by Y. Pauleau) p 155
[8] Pout J M et al 1983 Surface modification and alloying by laser, ion, and electron beams (New York and London: Plenum Press)

[9] Churumov A Yu, Zolotarevskii N Yu, Solonin A N and Zolotarevskii V S 2007 Izv. Vyssh. Uchebn. Zaved. Tsvetn. Metall. 3 50

[10] Churumov A Yu, Solonin A N and Zolotarevskii V S 2007 Izv. Vyssh. Uchebn. Zaved Tsvetn. Metall. 4 53

[11] Zolotarevskii V S, Zolotarevskii N Yu, Solonin A N et al. 2007 MITOM 11 94

[12] Solonin A.N., Churumov A Yu, Malinin R Yu et al 2007 Metals 6 94

[13] Kocks U F 1967 Canadian Journal of Phys. 45 737

[14] Goldstein M I and Farber B M 1979 Dispersion hardening of steel (M.: Metallurgy) p 208

[15] Vladimirov V I 1975 The physical theory of strength and plasticity. Point defects. Hardening and return (L.: LPI) p 120

[16] Shtrumel M A 1999 Strength of alloys. Part I. Defects of the lattice (Moscow: MISIS) p 384

[17] Trefilov V I, Moiseev V I and Pechkovsky E P 1987 Deformation hardening and destruction of polycrystalline metals (Kiev: Naukova dumka) 248

[18] Hall E O 1951 Proc. Phys. Soc. 64B 747

[19] Petch N J 1953 Iron Steel Inst. 74 25

[20] Ivanov Yu F, Kornet E V, Kozlov E V and Gromov V E Hardened structural steel: structure and strengthening mechanisms 2010 (Novokuznetsk: Izd. Sib. St. Univ.) 174

[21] Sevillano J G 1993 Mater. Sci. and Technol. 6 19

[22] Frost G J and Ashby M F Maps of deformation mechanisms (Chelyabinsk: Metallurgy)

[23] Orowan E. 1948 Inst. Metals. (London) 451

[24] Khornbogen 1986 Increase in strength of dispersed precipitates (Sat. scientific works. Trans. with him., Ed. V. Dal, V. Anton, Moscow: Metallurgy) 165

[25] Kocks U F 1967 Canadian Journ. of Phys. 45 737

[26] Starink M J and Wang S C 2003 Acta Mater 51 5131

[27] Starink M J, Wang P, Sinclair I and Gregson P J 1999 Ibid. 47 3855

[28] Esmaeili S, Lloyd D J and Poole W J 2003. Ibid. V 51 2243