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Deformation and Fracture of Hypereutectic Silumin Samples with a Surface Modified with an Intense Pulsed Electron Beam

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Abstract. Development of structural light-weight materials with necessary performance characteristics is an important task as they are used in mechanical engineering, aviation and space. It is known that macroproperties of a material depend on the structural-phase state at micro- and meso- level. One of the methods of transformation of the material structure is irradiation of the surface with an intense pulsed electron beam. The purpose of the paper is the analysis of the laws governing formation of a destruction surface structure of hypereutectic silumin AK10M2N in the as-cast state and in the state after exposure to a pulsed electron beam. Deformation of silumin samples was carried out using the strain to failure method. Electron beam irradiation was carried out in the high-speed melting mode of the surface layer of samples prepared for tensile testing. As a result of the studies, it has been found that irradiation leads to formation of multiphase structure with micro- and nanoscale inclusions in the treated surface layer with a thickness up to 70 μm. An increase in strength (in 2 times) and plastic (in 1.8 times) properties of silumin irradiated with an electron beam has been revealed.

INTRODUCTION

Currently, one of the most popular materials in aircraft, ship and automotive building, instrument making and construction, are alloys of aluminum with silicon (silumins) [1]. The fact is conditioned upon low specific gravity, relatively high specific strength and corrosion resistance, as well as good fluidity of these alloys [2]. An obvious drawback of silumins is their high fragility associated with the presence of coarse silicon inclusions and second phase particles of the casting origin [1-3]. It is known that macroproperties of a material depend on the structural-phase state at the micro- and meso- level [4-8]. One of the promising methods for transforming the structure of metals and alloys, including silumin, is high-speed heat treatment based on the use of concentrated energy fluxes (continuous and pulsed electron beams, plasma flows, powerful ion beams, laser beams, ion implantation, etc.) [9-12]. In a number of works [13–22], it has been shown that irradiation of silumin with a pulsed electron beam in the melting mode of the surface layer is accompanied by formation of a submicro- nanocrystalline multiphase structure with high tribological properties.

The purpose of the paper is the analysis of the laws governing formation of the fracture surface structure of hypereutectic silumin AK10M2N in the as-cast state and in the state after exposure to an intense pulsed electron beam.

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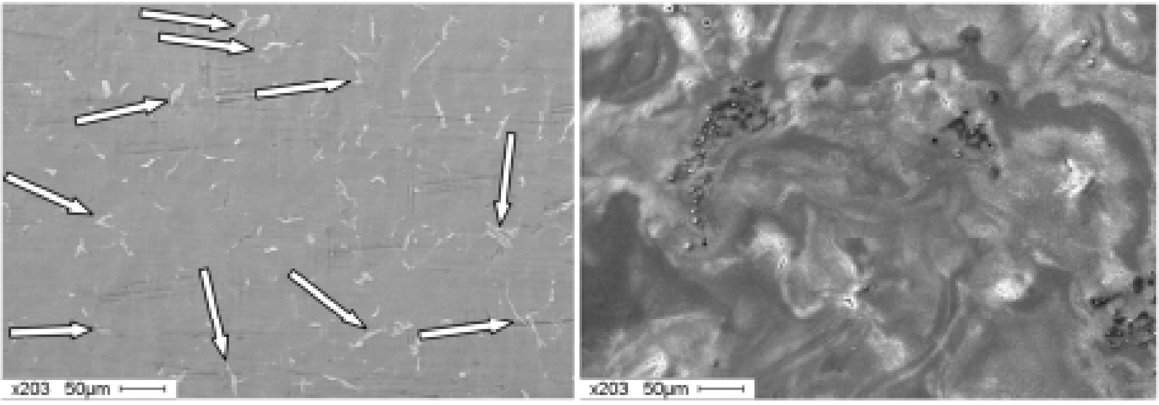
MATERIAL AND METHODS

The object of the investigation was as-cast AK10M2H silumin of the following composition (wt %): 9.5–10.5 Si, 2.0–2.5 Cu, 0.8–1.2 Ni, 0.9–1.2Mg, >0.6 Fe, >0.05 Mn, >0.05 Ti, >0.05 Pb, >0.06 Zn, >0.01 Sn, and Al for balance. The surface of the plates was irradiated with a high-current pulsed electron beam in a «SOLO» setup [23]. Irradiation parameters: accelerated electron energy 17 keV, pulse duration of the electron beam 150 μs, number of pulses 3, pulse repetition rate 0.3 s^{-1}, electron beam energy density 25 J/cm^2. Proportional flat samples were used in the tests. Tensile testing of the samples was carried out on the INSTRON 3386 installation (tensile rate 2 mm/min) with simultaneous fixation of the deformation fields using the VIC-3D optical measuring system [24]. Investigation of the silumin structure in the initial state and after modification was carried out by scanning (Philips SEM 515) [25] and transmission diffraction (JEM-2100F) [26] electron microscopy. Analysis of the elemental composition of samples was carried out using SEM/EDAX methods [25].

RESULTS AND DISCUSSION

The material under study belongs to silumins with a pre-eutectic composition. Therefore, in the as-cast state, the alloy will be a multiphase material, and will consist of grains of an aluminum-based solid solution, eutectic grains, inclusions of silicon and intermetallics of various compositions [2]. A typical electron microscopic image of the as-cast AK10M2N silumin structure is shown in Fig 1a. Inclusions of various shapes and sizes, which are intermetallics, are clearly visible on the presented image (inclusions are indicated by arrows).



(a) (b)

FIGURE 1. The structure of AK10M2N silumin in the as-cast state (a) and after irradiation with an intense pulsed electron beam (b)

Irradiation of the surface of silumin samples with an intense pulsed electron beam with the aforementioned parameters leads to high-speed melting of the surface layer and its subsequent rapid solidification. A typical image of the resulting structure is shown in Fig. 1b and Fig. 2. A feature of high-speed heat treatment, which is implemented upon irradiation of metals and alloys with an intense pulsed electron beam, is an ultrahigh heating and cooling rate (up to 10^9 K/s) [11]. Short lifetimes of the material surface layer in the liquid state impede the melt homogenization process. As a result, the heterogeneity of the distribution of alloying elements in the surface layer of silumin is preserved. This explains the formation of the phase contrast on electron microscopic images of the silumin surface obtained using scanning electron microscopy methods (Fig. 1b).

The ultrahigh cooling rate of the molten layer leads to the formation of a micro- and nanoscale structure of cellular crystallization, a typical image of which is shown in Fig. 2. The sizes of crystallization cells vary within 200–400 nm (Fig. 2a). The cells are separated by interlayers of the second phase (Fig. 2b). X-ray microspectral analysis shows that the interlayers are formed mainly by atoms of silicon, copper, iron, and magnesium. Formation of two types of cells has been revealed using methods of transmission electron microscopy. Firstly, the cells formed by an aluminum-based solid solution (Fig. 3a, denoted by α). These cells contain particles of predominantly roundshaped silicon with a size of a few nanometers. Secondly, the plate-shaped eutectic cells (Fig. 3a, denoted by α+β). The transverse dimensions of silicon and aluminum plates in the eutectic vary within 50-70 nm).

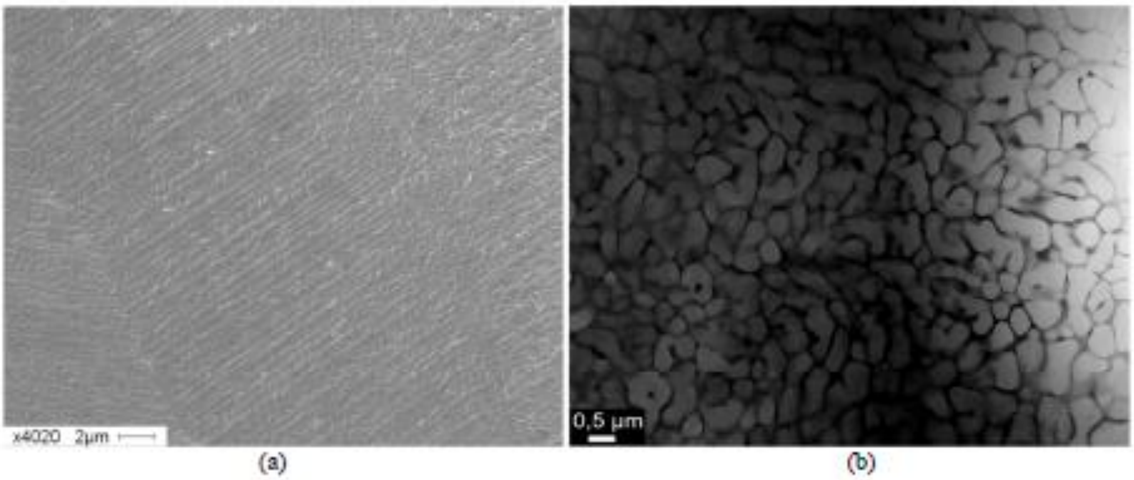


FIGURE 2. The structure of AK10M2N silumin after irradiation with an intense pulsed electron beam. Images were obtained using methods of scanning (a) and transmission (b) electron microscopy.

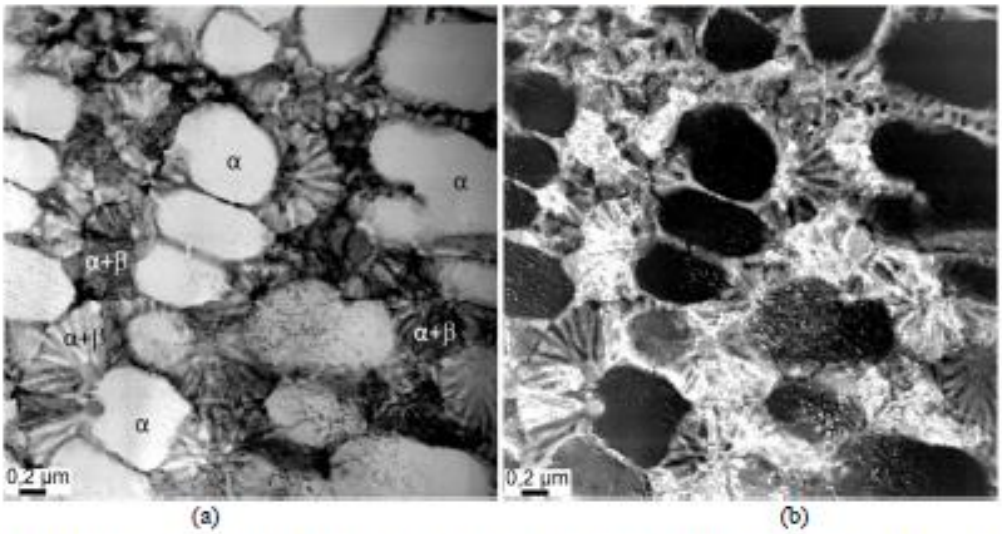


FIGURE 3. The structure of AK10M2N silumin after irradiation with an intense pulsed electron beam; a - is the bright field; b - is the dark field. Images obtained using STEM methods.

It is obvious that an essential transformation of the surface layer structure of silumin will contribute to a change in plastic and strength properties of the material. Indeed, mechanical tensile tests have revealed an increase in strain at break (in 2 times) and tensile strain (in 1.8 times) of silumin irradiated with an electron beam.

Investigations of the fracture surface of silumin samples in as-cast and irradiated states have revealed physical reasons for a multiple increase in mechanical properties of silumin. The analysis of the results presented in Fig. 4 and Fig. 5 shows that irradiation of silumin with a pulsed electron beam leads to the formation of a surface layer with a thickness of (35–40) µm, the fracture of which has a faceted structure characteristic of viscous fracture of a material [27]. Dimensions of the facets vary within (3-4) microns (Fig. 5). The fracture surface of as-cast silumin samples has a rougher structure (Fig. 4a). Brittle cleavage areas are found along with ductile fraction facets.

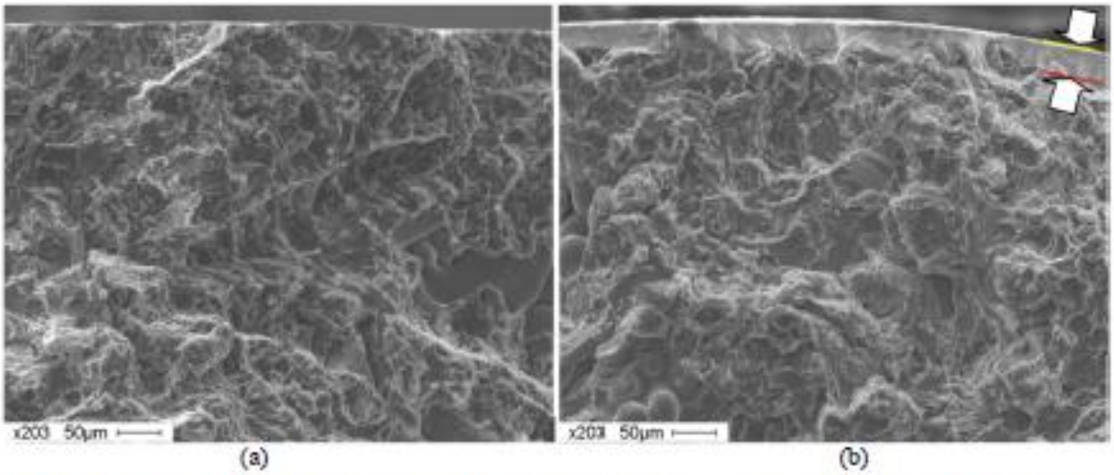


FIGURE 4. The structure of the fracture surface of AK10M2N silumin in the as-cast state (a) and after irradiation with an intense pulsed electron beam (b). In (b), arrows indicate the modified layer.

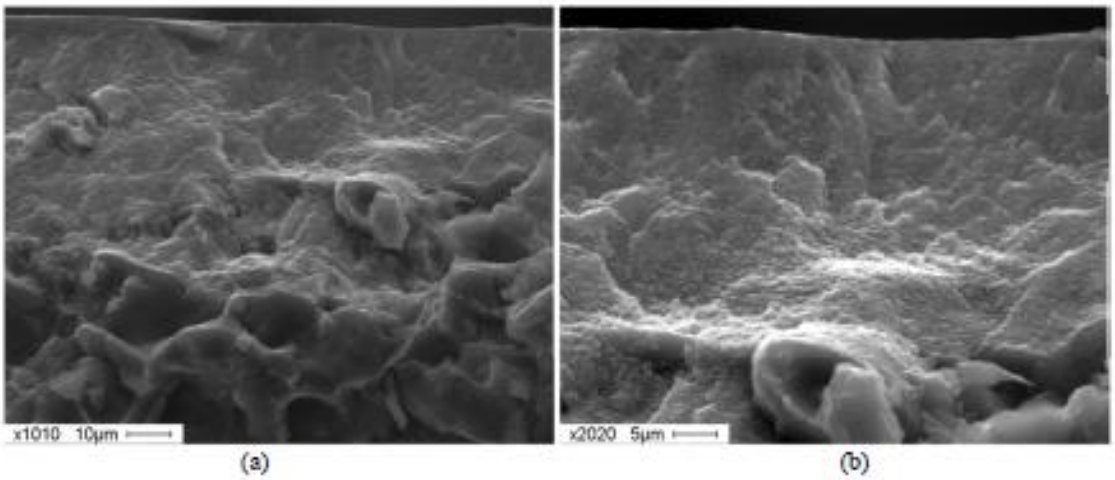


FIGURE 5. The structure of the fracture surface of AK10M2N silumin irradiated with an intense pulsed electron beam.

CONCLUSION

1. It has been established that irradiation of AK10M2N silumin with an intense pulsed electron beam allows forming surface layers with a multiphase submicro- nanocrystalline structure.
2. Tensile tests of proportional flat samples of AK10M2N silumin irradiated with an electron beam have revealed an increase (relative to the as-cast state) of the strain at the break by 2 times and the tensile strain in 1.8 times.
3. It has been shown that the main reason for the increase in strength and plastic properties of silumin, revealed during tensile tests, is the formation of a surface layer as a result of irradiation with a pulsed electron beam, deformed under the ductile fracture mechanism.

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