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Wear Resistance Evolution of Al-Si Aluminium Alloy after Electron Beam Processing

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Abstract. The perspective materials for a wide spectrum of work-pieces being used in all fields of industry are the cast aluminium alloys of Al-Si. However, the alloys have some disadvantages, that's why the techniques of alloy surface processing by energy fluxes to impart the new physico-mechanical properties are studied. In our research the technique of irradiation of Al–5 wt % Si–2 wt % Cu alloy surface by pulsed electron beam is considered. As a result of studies it was established that after electron beam processing at energy density of electron beam of 10 J/cm^2 the wear resistance of the alloy increased by 29% at pulse duration of 50 μs and by 32% at pulsed duration of 200 μs. It was also determined that due to high-rate heating of the surface as a result of electron beam irradiation a structure of high-rate crystallization of dendritic-cellular type is formed in the alloy bulk adjacent to a silicon plate. The results of the investigations into fine structure of Al–5 wt % Si–2 wt % Cu alloy make it possible to suggest that nanodimensional structure being developed will be an obstacle for crack distribution changing the kinetics of silicon plate fracture and, thereby, decreasing in the level of sample's abrasive wear.

INTRODUCTION

Aluminium and alloys based on it are perspective and the most abundant of industrial metals. It is second to ferrous metals in volume of production and scope of application, but aluminium ranks the first among all metals in distribution in nature. Its content in the earth crust is about 8%. However, in spite of its wide application there is a number of disadvantages seriously limiting its further use in many fields [1]. The possibilities of surface processing in order to alloy the material with other chemical elements by different energy beams including the pulsed electron beams were studied. These techniques are highly urgent because the energy beams generate immense inhomogeneities of distribution of temperature fields in material surface layers. These result in super-rapid melting, mixing and high-rate crystallization and, as a consequence, the increase in physico-mechanical characteristics of aluminium alloys [2–5].

Nowadays, cast aluminium Al-Si alloys take the leading places due to their high specific strength, low coefficient of heat expansion, excellent casting characteristics and good corrosion resistance [6]. Therefore, Al-Si alloys are widely used in the production of pistons, pulleys, cylinder liners, rocker arms substituting a traditional cast iron/steel in automobile and aircraft industry [7, 8]. In spite of all advantages of the alloys they have some disadvantages. Many research teams work to improve the physical and mechanical characteristics of Al-Si alloys. Multi-phase composites based on Al-Si are created. The problems of plastic deformation effect on tribological characteristics of $AlSi_9Cu_3$ alloy [7] were studied. In the research [9] the effect of alloying elements and rate of crystallization on the structure and mechanical properties of eutectic Al-Si alloys was detected. It is well known that

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mechanical properties of aluminium alloys depend on the characteristics of microstructure such as morphology and dimension of structural constituents. The experimental results of other researchers show that electron beam processing (EBP) plays important role in determining the phase composition of metal structure. It results in homogenization of surface layers and the decrease in defect of crystal structure [10–16].

Our research deals with the effect of electron beam processing on variation in wear resistance of Al–5 wt % Si–2 wt % Cu cast aluminium alloy and the reasons of factors contributing to it.

RESEARCH MATERIALS AND METHODS

The cast alloy Al–5 wt % Si–2 wt % Cu was used in this research. The results of micro-X-ray spectral analysis specify the following chemical composition of the alloy: 4.0–6.0 Si, 1.5–3.5 Cu, up to 0.5 Ni, 0.2–0.8 Mg, up to 1.3 Fe, 0.2–0.8 Mn, 0.05–0.2 Ti, up to 1.5 Zn; balance Al, wt %. The samples had the form of parallelepiped with the sides of $15 \times 15 \times 5$ mm in size.

The irradiation of samples by intense pulsed electron beam was performed at setup SOLO [17]. The electron beam parameters used in processing of Al–5 wt % Si–2 wt % Cu cast aluminium alloy are presented in Table 1.

The studies of elemental and phase composition, state of defective substructure were carried out by the methods of scanning electron microscopy (device Philips SEM-515), transmission electron diffraction microscopy (device JEM 2100F, JEOL), and X-ray phase analysis (X-ray diffractometer Shimadzu XRD 6000). The tribological properties of the material were characterized by wear resistance (device TRIBOtester, Pin-On-Disc type). Testing was carried out in the conditions of dry friction at the following parameters: normal load 2 N, speed of sample rotation 25 mm/s, distance travelled 100 m, track radius 2 mm, counterbody—6 mm diameter ball made of hard alloy VK7.

RESEARCH RESULTS AND DISCUSSION

In studying the tribological characteristics of Al–5 wt % Si–2 wt % Cu alloy the parameter of wear "k" was used that is the value reciprocal to wear resistance. The studies showed that the irradiation of Al–5 wt % Si–2 wt % Cu cast aluminium alloy by high intensity electron beam with energy density of 10 J/cm^2 and pulse duration of 50 and 200 μs results in the decrease in wear parameter k to 0.78×10^{-3} mm^3/N·m and 0.75×10^{-3} mm^3/N·m respectively, the wear parameter of the alloy in as received state is 1.1×10^{-3} mm^3/N·m. The obtained results allow to make a conclusion that after electron beam processing the wear resistance of Al–5 wt % Si–2 wt % Cu aluminium alloy increases by 29–32% depending on the duration of electron beam pulse.

The studies of samples irradiated by electron beam showed that at energy density of electron beam of 10 J/cm^2 independent of the duration of beam pulse (50 or 200 μs) the structure of processing surface (Fig. 1) is practically not different from that of the alloy in as received state. The micropores and inclusions of the second phase of various shapes and dimensions are present.

The studies performed by the methods of transmission electron diffraction microscopy enabled to reveal the following reasons of the increase in wear resistance of Al–5 wt % Si–2 wt % Cu aluminium alloy in the given state. Figure 2 shows the results of STEM analysis (a) and micro-X-ray spectral analysis (b) of surface layer structure of Al–5 wt % Si–2 wt % Cu alloy irradiated by pulsed electron beam.

Analyzing the results presented in Fig. 2 it may be noted that the high-velocity thermal effect initiated by the pulsed electron beam results in the formation of structure of high-velocity crystallization of dendritic-cellular type.

TEM analysis results of foil's portion are shown in Fig. 3.

TABLE 1. Processing parameters

The energy density of the electron beam, J/cm^2	Accelerated electron energy, keV	The duration of the electron beam pulse, μs	Number of pulses	Pulse repetition rate, s^{-1}	Residual gas pressure (argon) in the working chamber of the installation, Pa
10	17	50 / 200	3	0.3	2×10^{-2}

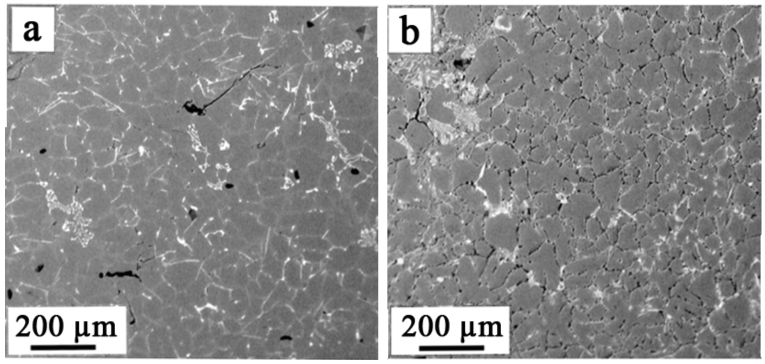

FIGURE 1. Structure of samples surface of Al–5 wt % Si–2 wt % Cu alloy irradiated by pulsed electron beam at duration of beam pulse of 200 (a) and 50 µs (b); the energy density of electron beam 10 J/cm^2.

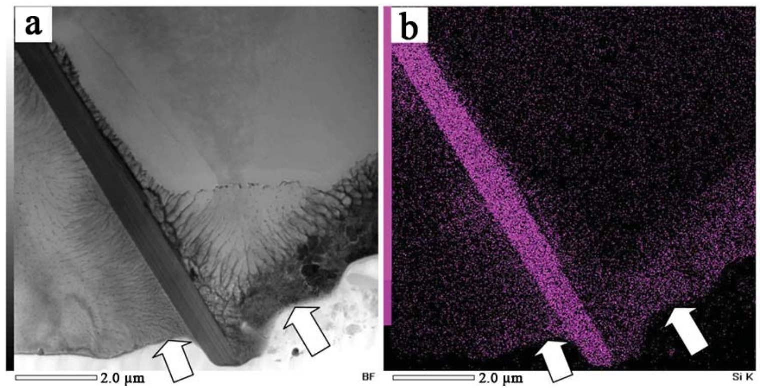

FIGURE 2. STEM image of surface layer structure of Al–5 wt % Si–2 wt % Cu alloy irradiated by electron beam with parameters of 10 J/cm^2, 50 µs, 3 pulses (a) and the image of the layer obtained in characteristic X-ray radiation of silicon atoms (b). Arrows designate the irradiation surface.

The analysis of microelectron diffraction pattern (Fig. 3b) and dark-field images (Figs. 3c, 3d) shows that crystallization cells are formed by solid solution based on aluminium, the silicon particles locate on the boundaries of aluminium cells. The sizes of crystallization cells vary in the limits from 40 to 100 nm; these of silicon particles—5–10 nm. The silicon interlayers forming the structure of lamellar eutectic (Figs. 3a, 3d) vary in the limits 15–25 nm. It is clearly seen in Fig. 4 that in the surface layer of the sample irradiated by electron beam the fragmentation of $FeSi_2$—phase plate into several fragments of rounded (globular) shape whose sizes vary in the limit of 200–300 nm is observed. It may be expected that the fragmentation of iron silicide plates and the globularization of fragments will contribute to the increase in wear resistance of Al–5 wt % Si–2 wt % Cu alloy as well.

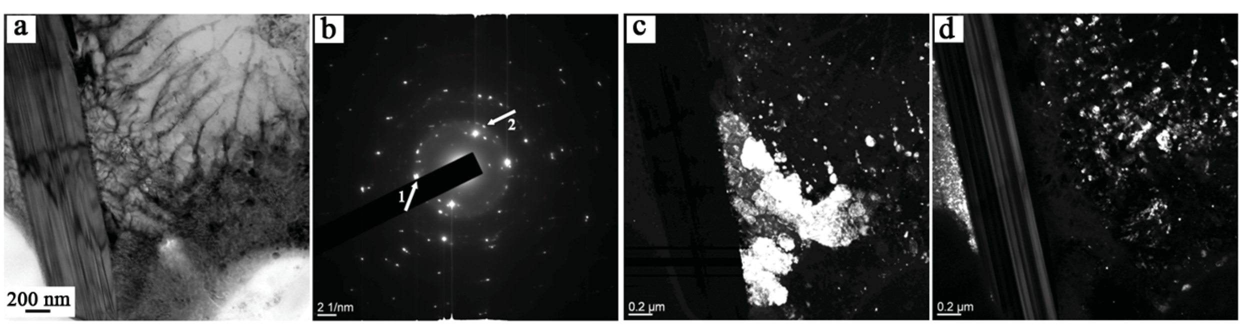

FIGURE 3. TEM image of surface layer structure of Al–5 wt % Si–2 wt % Cu alloy irradiated by pulsed electron beam 10 J/cm^2, 50 µs, 3 pulses: (a) bright field; (b) SAED; (c) dark-field obtained in closely located reflections [200]Al and [220]Si (reflection 1 on (b)); (d) dark-field obtained in reflection [220]Si (reflection 2 on (b)).

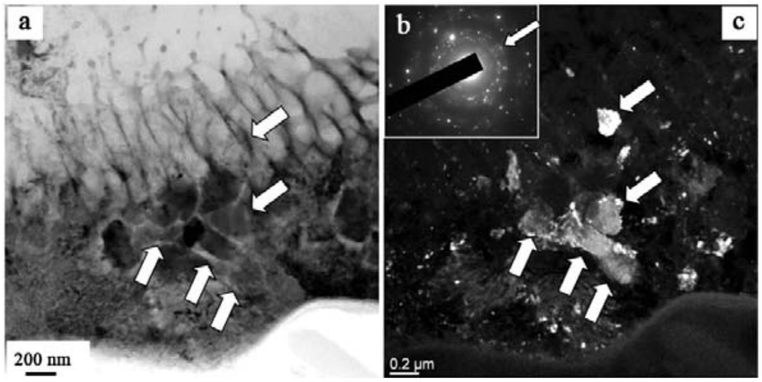

FIGURE 4. TEM image of surface layer structure of Al–5 wt % Si–2 wt % Cu alloy irradiated by pulsed electron beam (10 J/cm^2, 50 μs, 3 pulses); (a) bright field; (b) SAED; (c) dark field obtained in reflection [102]$FeSi_2$ (the reflection is designated by the arrow in (b)); in (a) and (c) $FeSi_2$ particles are designated by arrows.

CONCLUSION

In the research the studies of the wear resistance and the structure of Al–5 wt % Si–2 wt % Cu cast aluminium alloy being formed as a result of the processing with intense electron beam were carried out. The results of wear resistance measurement show that after electron-beam processing the wear resistance increases by 29–32%, depending on the duration of electron beam pulse. The investigations into fine structure of Al–5 wt % Si–2 wt % Cu alloy make it possible to conclude that one of the reasons of the increase in aluminium alloy wear resistance at the given mode of irradiation is the formation of a shell around the silicon crystallites. The shell is formed at high-rate crystallization of the adjacent aluminium layer enriched by silicon. The nanodimensional structure being created around brittle crystallites of silicon will be an obstacle for microcrack propagation, changing the kinetics of silicon plate fracture and, thus, decreasing in the level of sample's abrasive wear.

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