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INVESTIGATION OF THE STRUCTURE AND PROPERTIES OF AK5M2 ALLOY FOLLOWING SURFACE MODIFICATION WITH TITANIUM AND ELECTRON BEAM IRRADIATION

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The AK5M2 aluminum alloy was investigated following surface modification involving deposition of a titanium film with subsequent electron beam irradiation. The strength characteristics of the alloy according to tension to failure are determined. Changes in the crystal lattice period of the Al and Al_3Ti phases depending on the electron beam energy density are investigated and analyzed. Based on the experimental results, the most effective modes of electron beam processing were selected to increase the obtained mechanical properties of the alloy.

Keywords: AK5M2 alloy, Ti film deposition, electron beam processing, tensile strength, yield strength, crystal lattice period.

INTRODUCTION

Modification of the properties of the surface layers of light metals and alloys, such as aluminum alloys with silicon [1], remains a relevant task [2], which is associated with the widespread use of these materials in industry, for example, in the automotive industry [3]. During the operation of parts made of various metals and alloys, it is primarily the surface of the material that bears the load. This leads to higher requirements for the characteristics of the surface layers of parts than for their core. In this connection, it is especially important to ensure high reliability and wear resistance. The factors determining the efficiency of the surface layer of parts are: strength and hardness of the hardened zone; uniformity of structure and properties; high resistance to fracture and cracking [4]. Currently, in the field of physical materials science, much attention is paid to improving the properties of metals and alloys due to their processing with concentrated energy flows [5]. Methods of modifying surface properties include treatments with ion beams, plasma, ultrasound, etc. Here, one of the most effective and environmentally friendly methods is electron beam irradiation (EBI) [6, 7]. The advantages of EBI in comparison with other modification methods include high-energy efficiency, higher uniformity of energy density across the flow section, good reproducibility of pulses and high frequency of their repetition.

Another method for alloying the surface layer consists in spraying a thin film onto the surface of the material and then transferring the film with the surface layer (substrate) using vacuum-arc remelting (VAR) [8]. As contemporary studies show [9, 10], the maximum effect in modifying the surface layers of metals and alloys can be achieved by using complex processing to combine energy deposition methods. Such innovative processing methods can be used to increase the surface strength properties of materials and alloys by altering the structural and phase states that occur when combining energy deposition methods.

The aim of the present work is to study the structure, phase composition and mechanical properties of the AK5M2 alloy, which has been superficially modified with a titanium film, followed by electron beam irradiation under various modes.

METHODS OF STUDY

The base material used for the research was the standard aluminum alloy AK5M2 (GOST 1583–93) having the following chemical composition, wt.%: 4.0 – 6.0 Si; 1.5 – 3.5 Cu;

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< 1.5 Zn; < 1.0 Fe; < 0.5 Ni; 0.2 – 0.8 Mn; 0.05 – 0.20 Ti; 0.2 – 0.8 Mg; the remainder Al.

The composite material was obtained by the vacuum-arc method at the "KVINT" automated vacuum ion-plasma facility [11]. A titanium film with a thickness of 0.5 – 1.0 μm was sprayed using an arc evaporator. In this case, the sample for spraying was placed opposite the evaporator. The deposition of the titanium film was carried out without rotating the sample according to the following setup parameters: electrodynamic resistance current of the arc evaporator $I_a = 80$ A; starting current $I_s = 20$ A; nominal current $I_n = 135$ A; offset voltage $U_{cm} = 35$ V; residual gas pressure in the working chamber of the installation $p = 0.3$ Pa; spraying time $t = 10$ min.

Subsequent irradiation with a pulsed electron beam was conducted at the "Solo" facility [12]. Irradiation parameters: accelerated electron energy $U = 17$ keV; electron beam energy density $E_s = 10$, 20, 30, 40, 50 J/cm^2; pulse duration $t = 200$ μsec; number of pulses $n = 3$; pulse repetition rate $f = 0.3$ sec^{-1}; residual gas pressure (argon) in the working chamber of the installation $p = 2 \times 10^{-2}$ Pa. Using such optimal EBI parameters, a modified layer is formed in gradient-, multi-element-, multiphase- and nanostructured states offering unique properties [13].

Mechanical tests of alloy samples were carried out by uniaxial stretching on an INSTRON 3386 testing machine with a constant speed of 1.25 mm/min. The samples for these tests were made in the form of proportional blades having a thickness of 2.48 mm, a width of 9.1 mm, and a working part length of 15.0 mm. Samples of the AK5M2 alloy in the cast (initial) state, as well as samples of composites following spraying of titanium film subsequent EBI, were subjected to uniaxial stretching according to the modes: (*1*) $E_s = 10$ J/cm^2; (*2*) $E_s = 20$ J/cm^2; (*3*) $E_s = 30$ J/cm^2; (*4*) $E_s = 40$ J/cm^2; (*5*) $E_s = 50$ J/cm^2.

Studies of the state of the crystal lattice of phases were performed by x-ray phase analysis using a Shimadzu XRD 6000 diffractometer.

RESULTS AND DISCUSSION

The results of mechanical tests of cast alloy AK5M2 and the modified material obtained by vacuum arc spraying of titanium film and subsequent EBI are shown in Fig. 1.

The average value of the strength limit of the AK5M2 alloy in the cast (initial) state $\sigma_r = 118$ MPa (Fig. 1*a*). After spraying titanium film $\sigma_r = 155$ MPa, which is 31% higher than in the cast state. Analysis of the results of tensile tests of samples after deposition of the titanium film and subsequent EBI in various modes showed (Fig. 1*a*) that tensile strength is lower than the initial value by about 8 and 5%, respectively, following EBI in modes *2* and *4*. Following EBI in modes *1*, *3*, *5*, the tensile strength increases by about 16.5, 19 and 12%, respectively.

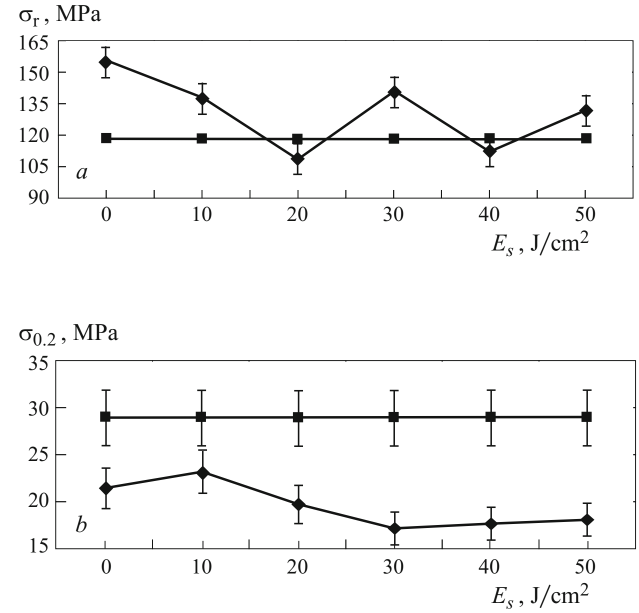

Fig. 1. Dependences of the strength limits (σ_r) and yield strength ($\sigma_{0.2}$) of composites on the electron beam energy density E_s at EBI: horizontal lines — properties of the base alloy AK5M2 in the cast (initial) state; $E_s = 0$ — state after spraying the film.

The yield strength values of the studied samples are shown in Fig. 1*b*. In the cast state, the yield strength of the alloy $\sigma_{0.2} = 29$ MPa. After spraying the titanium film $\sigma_{0.2} = 22$ MPa. Subsequent EBI of samples with a sprayed titanium film for various modes leads to a decrease in the yield strength regardless of the electron beam energy density. The maximum decrease in yield strength is observed after processing according to the regime *3* ($E_s = 30$ J/cm^2): $\sigma_{0.2} = 17$ MPa, which is 40% less than that of the sample in the cast state.

Figure 2 shows the deformation curves obtained as a result of uniaxial stretching of AK5M2 alloy samples in different states. Analysis of the data in Fig. 2 shows that the fracture stress of the samples increases simultaneously with an increase in the plasticity characteristics following deposition of the titanium film and subsequent EPO according to mode *3*.

After tensile tests conducted prior to fracture, the plasticity characteristics of the initial alloy and composite material — relative elongation (δ) and relative narrowing (ψ) [14] — were calculated. The results are shown in Fig. 3.

Relative elongation of the AK5M2 alloy sample in the cast state during the tear test $\delta = 6\%$. After applying the titanium film, the relative elongation (linear strain) of the composite material increased up to $\delta = 11\%$. Following deposition and EBI according to modes *1* and *3*, the linear strain increases to a lesser extent — up to 9 and 10%, respectively. Following EBI in modes *2*, *4* and *5*, no changes in the relative elongation of the samples within the measurement error were detected.

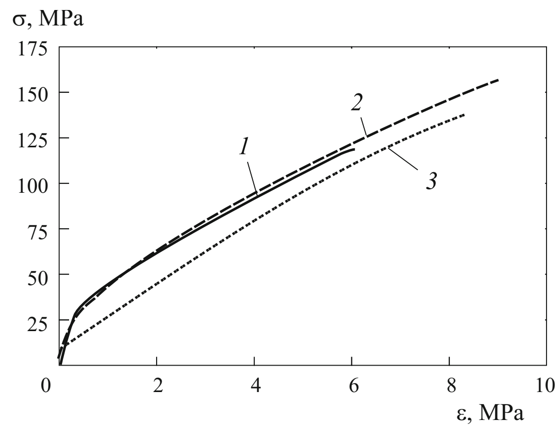

Fig. 2. Stress-strain diagrams $\sigma - \varepsilon$ for samples of AK5M2 alloy in cast state (*1*) and composites following deposition of titanium film on the alloy (*2*) and subsequent EBI at E_s = 30 J/cm^2 (*3*).

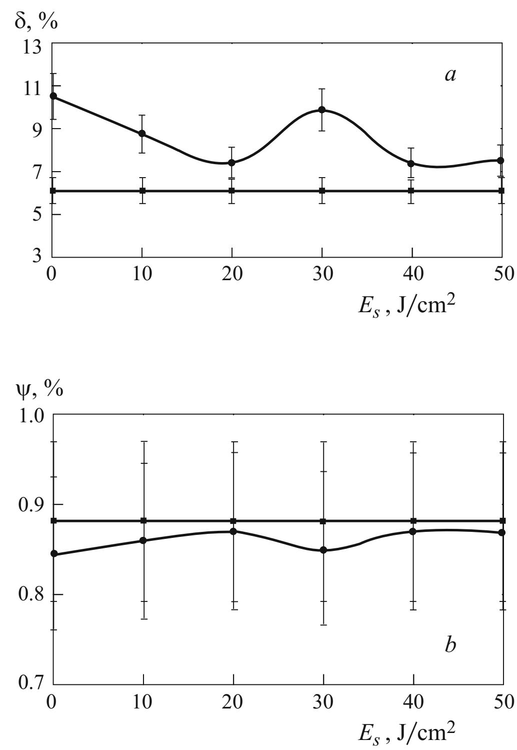

Fig. 3. Dependencies of the relative elongation (δ) and relative narrowing (ψ) of composites on the energy density of the electron beam E_s at EBI: horizontal lines — properties of the base alloy AK5M2 in the lithium (initial) state; E_s = 0 — state after film deposition.

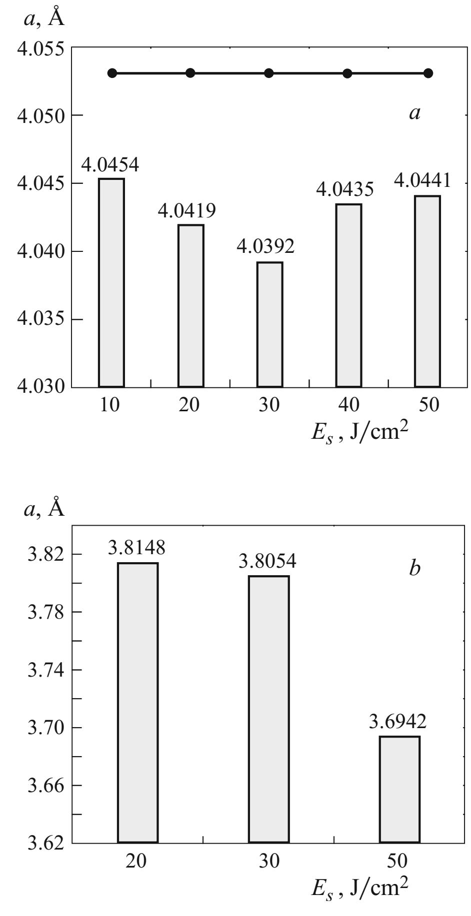

Fig. 4. Periods of the crystal lattice of a solid solution based on Al (*a*) and intermetallic Al_3Ti (*b*) after EBI: the horizontal line represents the lattice period of the phase in the AK5M2 alloy in the cast (initial) state.

The results of the evaluation of the relative narrowing of the samples are shown in Fig. 3*b*. It can be seen that in the cast state, the AK5M2 alloy has ψ = 0.880%, while after deposition with titanium film, ψ = 0.845%. After applying the titanium film and EBI according to modes *1* – *5*, the following values of residual narrowing were obtained (%): (*1*) ψ = 0.858; (*2*) ψ = 0.869; (*3*) ψ = 0.850; (*4*) ψ = 0.870; (*5*) ψ = 0.868. The analysis of the values of the relative narrowing of the composites showed that all of them are within the measurement error, i.e., changes in the energy density of the electron beam have practically no effect on the value of ψ.

Figure 4 presents the results of the evaluation of the crystal lattice periods of a solid solution based on Al and intermetallic Al_3Ti, obtained by x-ray phase analysis. Fig. 4*a* shows that the lattice period of the solid solution in the alloy AK5M2 in the cast state *a* = 4.0531 Å. After applying the titanium and EBI film, the lattice period decreases for all the studied modes. The minimum lattice period is observed after EBI according to mode *3*: *a* = 4.0392 Å. With a decrease in the period of the crystal lattice of an Al-based solid solution, compaction generally occurs, which in turn leads to changes in the properties of the material under study.

Figure 4*b* shows the changing period dynamics of the Al_3Ti phase crystal lattice. Only in three processing modes out of five were the changes in the lattice period found to be significant. As can be seen from the diagram, the formation of the Al_3Ti phase is facilitated by conducting EPO with an electron beam energy density of $E_s = 20$ J/cm^2 (a = 3.8148 Å), $E_s = 30$ J/cm^2 (a = 3.8054 Å) and E_s = 50 J/cm^2 (a = 3.6942 Å). There is an inversely proportional relationship of the period a with the value E_s. With an increase of E_s, the lattice period of the phase Al_3Ti decreases.

The period of the Si phase crystal lattice when irradiated with a pulsed electron beam $E_s = 10$ J/cm^2 is 5.4418 Å, which exceeds the period of its lattice in the initial state (a = 5.4391 Å). At E_s = 50 J/cm^2, the lattice period of the Si phase decreases to a minimum value of a = 5.4391 Å.

CONCLUSIONS

1. Based on the results of experimental studies of the AK5M2 alloy, after spraying a titanium film onto its surface with subsequent electron beam treatment according to various modes, a processing mode *3* was identified, which most effectively enhances the mechanical properties of the sample: energy of accelerated electrons $U = 17$ keV; energy density of the electron beam $E_s = 30$ J/cm^2; pulse duration $t = 200$ μsec; number of pulses $n = 3$; pulse repetition rate $f = 0.3$ sec^{-1}; pressure of residual gas (argon) in the working chamber of the installation $p = 2 \times 10^{-2}$ Pa.

2. The tensile tests of the composite prepared by sputtering a titanium film and subsequent irradiation according to mode *3* resulted in the highest tensile strength σ_r = 141 MPa, which is about 19% higher than the initial (after casting) value. At the same time, the yield strength of the alloy decreased to $\sigma_{0.2}$ = 17 MPa, i.e., by 40% as compared to the initial value. Relative elongation of the alloy δ = 10%, which is 60% higher than in the cast (initial) state (δ = 6%).

3. According to the results of x-ray phase analysis of an alloy with a sprayed titanium film and EPO according to the mode *3* (E_s = 30 J/cm^2), the following phases were identified: 99.31% solid solution based on Al and 0.69% Al_3Ti.

4. The crystal lattice period of an Al-based solid solution depends ambiguously on the energy density of the electron beam E_s. With an increase of E_s to 30 J/cm^2, it decreases monotonously to a minimum — a = 4.0392 Å. A further increase of E_s to 50 J/cm^2 leads to an increase in the lattice period to a = 4.0441 Å, which is lower than the lattice period of the cast alloy. The dependence of the Al_3Ti intermetallic lattice period on the electron beam density is inversely proportional: with an increase of E_s, the Al_3Ti lattice period decreases.

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