Formations of wear-resistant extended layers by combined electron-ion-plasma treatment on the surface of aluminium

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Formations of wear-resistant extended layers by combined electron-ion-plasma treatment on the surface of aluminium

O V Krysina, Yu F Ivanov, Yu Kh Akhmadeev, I V Lopatin, E A Petrikova and O S Tolkachev

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia

E-mail: krysina_82@mail.ru

Abstract. The study demonstrates that surface alloying of commercially pure A7 aluminum with titanium and copper through plasma-assisted vacuum arc deposition and electron beam irradiation provides the formation of Ti-Al and Cu-Al surface alloys whose hardness and wear resistance are several times greater than those of the initial material. The best result is attained with a Ti film 0.5 µm thick and a Cu film 1 µm thick after irradiation at a beam energy density of 10 J/cm² and pulse duration of 50 µs. At these parameters, the microhardness of the Ti-Al system increases by a factor of ≈4.2 after 50 pulses, and its wear resistance by a factor of ≈2.3 after 100 pulses. The microhardness of the Cu-Al system increases ≈3.2 times and its wear resistance increases ≈1.5 times after 3 and 50 pulses, respectively. The increase in the hardness and wear resistance of the Ti–Al system owes to the formation of AlTi, Al₃Ti, Al₂Ti, TiAl₃, and Al₅Ti₂ with a particle size no greater than 100 nm. The hardening phase in Cu-Al is Al₂Cu.

1. Introduction
The use of aluminum and its alloys is limited by their low hardness and wear resistance [1, 2]. The properties of metal materials can be improved through deposition of hard and wear-resistant coatings, surface modification by concentrated energy flows, saturation with metal and gas atoms, implantation, etc. [3-7], and also through bulk alloying and surface alloying via ion implantation, laser doping, plasma or ion beam treatment, etc. [8-15].

Here we analyze the structure and properties of commercially pure aluminum after electron-ion-plasma surface alloying with titanium and copper.

2. Material and research techniques
The substrate material was commercially pure A7 aluminum (0.16Fe, 0.15Si, 0.01Cu, 0.04Zn, 0.01Ti, balance Al wt%). The Al substrate was surface alloyed with Ti and Cu through vacuum arc deposition of a VT1-0 (Ti) or a M1 (Cu) film 0.5 and 1 µm thick and subsequent intense pulsed electron beam irradiation of the film–substrate system (3-100 pulses, 50 µs, 0.3 Hz, 17 keV, 10, 15, and 20 J/cm²) in a single vacuum cycle on the COMPLEX setup [16, 17]. After modification we analyzed the surface morphology and elemental composition of the alloyed layer (Philips SEM 515 microscope, EDAX ECON IV microanalyzer), its phase state (XRD 6000 diffractometer), defect structure (JEOL JEM 2100F microscope), microhardness (PMT-3 tester), and wear resistance (TRIBOtechnic device).
3. Results and discussion

The film-substrate system formed by plasma-assisted vacuum arc deposition reveals microdroplets (figure 1a), which can adversely affect its surface properties as they impair the film homogeneity and increase the surface roughness. After further irradiation, which provides surface alloying through liquid phase mixing, the film-substrate system has a rather smooth surface layer. The Ti-Al surface alloy shows no microdroplets after 50 pulses (figure 1b), and the Cu-Al surface alloy after 5 pulses.

![Figure 1. Surface of Ti–Al system before (a) and after irradiation with 50 pulses at 17 keV, 10 J/cm\(^2\), 50 µs, 0.3 Hz (b).](image)

During irradiation, the concentration of Ti (or Cu) in the surface layer decreases, suggesting the formation of a surface alloy based on Al and Ti (or Cu).

The phase state of the surface alloy depends on the beam energy density and number of pulses. The Ti-Al surface layer contains intermetallic compounds Al\(_3\)Ti, Al\(_2\)Ti, and TiAl\(_3\), and also titanium oxides TiO, TiO\(_2\) in addition to its main solid phase based on Al and α-Ti. The main hardening phase is TiAl\(_3\) whose maximum relative content (28.4 mass%) is reached after irradiation with 75 pulses at 10 J/cm\(^2\), 50 µs. The Cu-Al surface layer reveals Al\(_2\)Cu whose maximum relative content (∼36 mass%) is found after irradiation with 3 pulses at 20 J/cm\(^2\), 50 µs.

In the irradiated film–substrate system, irrespective of the alloying element (Ti or Cu), a gradient submicro-nanosized surface structure is formed.

In the Ti-Al system, the layer adjacent to the irradiated surface has a polycrystalline structure with grains of size 0.5-7 µm and second phase particles (Ti aluminide) of size 30-50 nm inside the grains (figure 2a). The layer at a depth of 3-15 µm is also polycrystalline (figure 2b). It represents Ti crystallites of size 150-700 nm in the Al matrix. The concentration of Ti atoms in this layer is 10 mass%. Likely, the layer is formed due to electron beam decomposition of the Ti film and its immersion into the molten Al layer.

The surface layer of the Cu-Al system has a cellular structure (figure 3a). The shape of cells changes from globular near the irradiated surface to dendritic in going deeper. The cell size also changes with depth: in the layer adjacent to the irradiated surface, the transverse size of cells is 150-180 nm, and at a depth of 10 µm, it is 230-240 nm. The cells are separated by second phase interlayers whose transverse size depends slightly on depth and measures 50-70 nm. The cells are formed by solid solution based on Al, and the interlayers by solid solution based on Cu and Cu aluminides. With depth from the irradiated surface, the cellular structure passes into a band substructure (figure 3a), and the latter into a structure with chaotically distributed round Cu particles in Al grains (figure 3b).
Figure 2. Structure of Ti-Al system after irradiation with 75 pulses at 10 J/cm², 50 µs. Film thickness is 0.5 µm.

Figure 3. Structure of Cu-Al system (arrow to film fragment) after irradiation with 3 pulses at 10 J/cm², 50 µm. Film thickness is 1 µm.

The microhardness and the wear resistance of the Ti-Al and Cu-Al surface alloys are several times greater than those of the initial material. The best result is attained with a Ti film 0.5 µm thick and a Cu film 1 µm thick after irradiation at 10 J/cm², 50 µs. At these parameters, the microhardness of Ti-Cu increases by a factor of ≈4.2 after 50 pulses, and its wear resistance by a factor of ≈3.2 after 100 pulses. The microhardness of Cu-Al increases ≈3.2 times after 3 pulses, and its wear resistance ≈1.5 times after 50 pulses.

4. Conclusion
Thus, our study demonstrates that surface alloying of commercially pure A7 aluminum with Ti and Cu through plasma-assisted vacuum arc deposition and electron beam irradiation provides the formation of Ti-Al and Cu-Al surface alloys whose hardness and wear resistance are several times greater than those of A7 aluminum. The microhardness and the wear resistance of Ti-Al are greater by a factor of
≈4.2 and 2.3, respectively, and those of Cu-Al by a factor of ≈3.2 and ≈1.5, respectively. The thickness of the surface-alloyed layers reaches 20-30 µm. In the Cu-Al system, the modified layer has a gradient submicro-nanosized multiphase structure with cells formed by Al-based solid solution and with Cu and Cu aluminide interlayers along their boundaries. In the Ti-Al system, the Ti film is decomposed by irradiation such that its fragments are immersed in molten aluminum with the formation of a subsurface layer enriched in Ti. Such electron-ion-plasma surface alloying is realized in a single vacuum cycle on the COMPLEX setup designed and operated at the Institute of High Current Electronics SB RAS (Tomsk, Russia).

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