ELECTRON-BEAM FACILITY "RITM-SP" FOR POLISHING AND SURFACE ALLOYING ON COMPLEX-SHAPED SURFACES

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Аннотация: Полировка металлических поверхностей импульсным электронным пучком дает ряд уникальных возможностей, недостижимых другими методами полировки, являясь при этом высокотехнологичной и экологически безопасной технологией. Кроме сглаживания микрорельефа, электронно-пучковая полировка обеспечивает высокую степень очистки поверхностного слоя, что повышает коррозионную стойкость поверхности. В настоящее время электронно-пучковая полировка является наиболее перспективной среди технологий финишной обработки металлических изделий сложной формы. Сочетание в едином вакуумном цикле электронно-пучкового поверхностного плавления, нанесения пленок и последующего их сплавления с основой электронным пучком, реализуемое в установках «РИТМ-СП», позволяет формировать дорогостоящие наноструктуированные сплавы на поверхности изделий из дешевых конструкционных металлов и сплавов. При этом за счет короткоимпульсного режима обработки не происходит значительного нагрева изделия в объеме материала, что позволяет сохранять неизменной форму обрабатываемых изделий.

Body text of the paper:

Liquid-phase mixing of film-substrate systems with pulsed intense powerful beams is an efficient method for formation of surface alloys. Unlike the commonly used PVD and CVD techniques, the method of liquid-phase mixing is free from problems of poor film adhesion and delamination. The alloyed layer achievable is much thicker than 1 μm which is too problematic to be achieved with the use of high-dose ion implantation. At the Institute of High-Current Electronics (Tomsk, Russia), the novel technique has been developed for the surface modification of materials, particularly for the surface alloying, based on application of the low-energy and high-current electron beam of microsecond duration [1]. A set of interesting investigations on alloying with a similar source has been carried out as well by research group at the Key Laboratory of Materials Modification (Dalian, China). In comparison with the other sources being employed for the surface alloying, this one has some attractive characteristics. The major appealing features of the source for the electron-beam surface treatment (EBEST) are an easy control, large beam diameter, and X-ray safety. The paper reviews briefly the EBEST technique for surface alloying and the results characterization of surface alloys based on EBEST of two-element film-substrate systems being of practical interest.

A surface under treatment is prepared preliminarily with magnetron deposition of a film onto a substrate. EBEST precedes deposition *in situ*, which provides high adhesion of a film due to high-temperature heating (above the meting point) by the electron beam. After film deposition, a surface is treated with EBEST again to mix a film with a substrate bulk material. Figure 1 presents the idea of the approach under consideration.

Schematic diagram of the EBEST source can be seen in Figure 2. Fundamentals of electron-beam generation are as follows [2]: On the first stage, a column of plasma as dense as 10^{12} to 10^{13} cm^{-3} is forming in the space between electron gun cathode *1* and electron beam collector *7*. To provide this, a high-current reflected discharge is igniting in the working gas (argon) between the cathode *1*, collector *7* and ring anode *3*. Once the plasma column has been formed, an accelerating voltage pulse of the 20-ns front edge is applying to the cathode *1*. Due to the high conductivity of the plasma column, almost whole the accelerating voltage is applied to the cathode sheath layer of 1 to 2 mm in thickness. This leads to a sharp increase in electric field at tips of the multi-wire cathode and to the explosive electron emission there. The cathode plasma *2* is dense in comparison to the anode plasma *4*, and the double electric layer (DEL) *5* appears to separate the plasmas. As a result, the accelerating voltage is localized in the DEL. Electrons are emitted by the cathode plasma, are accelerated in the DEL, and are transported through the anode plasma channel to a collector where a sample under treatment is placed. Additionally, a guide magnetic field, which is generated with a solenoid *8*, is used to transport the beam. The electron gun is connected with a working chamber equipped with a manipulator to rotate a sample between both the magnetron and EBEST working areas.

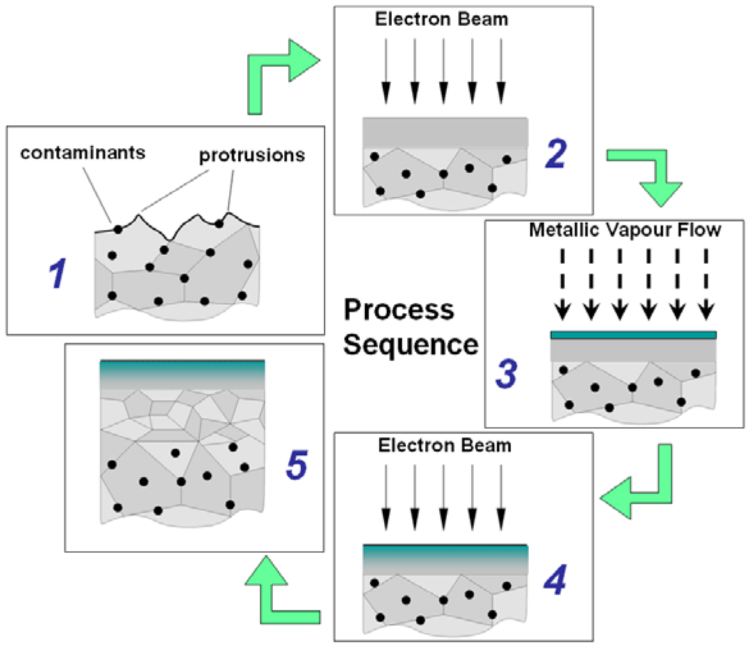


Figure 1. The schematic diagram of a process sequence, from ***1*** to ***5***, forming (***5***) a refined surface alloy on (***1***) an originally rough and contaminated surface.

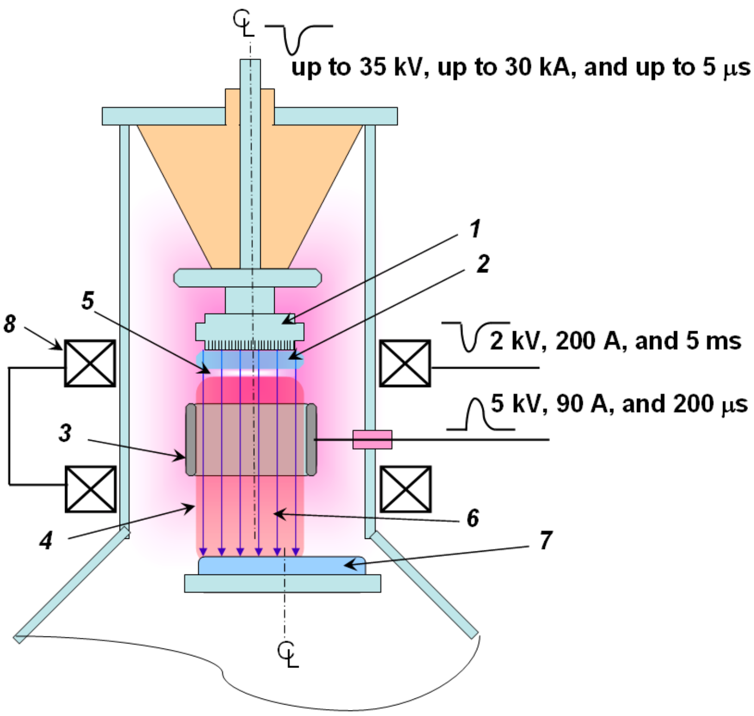


Figure 2. The schematic diagram of the EBEST facility where components are shown as follows: ***1*** the explosive-emission cathode, ***2*** the cathode plasma, ***3*** the anode, ***4*** the anode plasma, ***5*** the double electric layer, ***6*** the electron beam, ***7*** a sample under the treatment, and ***8*** the guide magnetic field coils.

The electron gun operates successfully at acceleration voltages within 20 to 40 kV. The beam diameter could be varied up to 11 cm. The 30-kA beam current could be transported with insignificant losses at a distance of up to 30 cm. Pulse duration of the electron beam could be varied 0.8 to 3 μs, and energy density is ranging from 1 to 15 J/cm^2. EBEST sources are reliable, X-ray safe and easy in control. At the moment, the similar equipment are produced by Sodick Co., Ltd. In Japan under the license by IHCE SB RAS (Fig. 3). The new "RITM-SP" facility is based on the EBEST source and one or two magnetrons for film deposition.

As a result of EBEST, the surface becomes shining but it is not a unique positive effect of EBEST. The most important feature of the treatment is the ultimate cleaning of the surface layer being as thick as few micrometers. Ultra-high purification is a result of short-term heating of a surface in vacuum up to temperatures exceeding sufficiently the melting point of a material under treatment. Super-fast cooling of a melted layer leads to formation of a nano-crystalline structure.

Figure 3. The photo of the PF-32A facility developed by "Sodick Co., Ltd.", "ITAC Ltd.", and IHCE SB RAS in collaboration.

Alternation of film deposition and EBEST turns out to be a powerful tool in surface engineering. On the one hand, a fine alloy can be formed exactly there where it is necessary. On the other hand, extreme conditions of the treatment allow forming non-equilibrium alloys being unattainable with traditional methods of metallurgy. Any bulk–surface system is unique in know-how and a purposeful R&D is required to create it. As an example, let’s consider the Zr/Ti/Ti-6Al-4V system. The Ti-6Al-4V alloy is the most common metallic biomaterial. The major issue limiting long-term stability of implants made of this alloy is a danger of release of toxic Al and V ions in surrounding body tissue. To deplete the content of toxic Al and V in the surface layer of Ti-6Al-4V, an attempt of surface alloying with Zr was done. Zirconium is a good candidate for alloying because it is biocompatible like titanium, enhances both the corrosion resistance and strength of Ti, and, moreover, has unlimited solubility in α- and β-Ti. The latter simplifies appreciably the task of formation of surface Ti-Zr alloys by pulsed melting. The uniform surface alloy was fabricated with Zr(20nm)/Ti(20nm)/…/ Zr(20nm)/Ti(20nm)/Ti-6Al-4V system where the total films thickness was 480 nm. Homogeneous liquid-phase mixing of all Ti/Zr nano-films and diffusion of Zr into the substrate up to a depth of 1 μm takes place after a single-shot pulsed melting (3.5 J/cm^2) (Fig. 4). The surface layer of depth of about 0.5 μm is free of Al and V and has a single-phase α(Ti,Zr)-solid solution structure containing about 30 at.% of Zr as it was revealed by XRD and Auger analyses. The further vacuum annealing (500°C, 2 hours) leads to increase in depth of the alloyed layer up to 1.2 μm and its enrichment with O and C contaminates. The behavior of concentration profiles of Zr and Ti before and after annealing is the same; and the surface layer of thickness of 0.5 μm is free of Al and V. AFM surface analysis of Ti-Zr alloy revealed its nano-crystalline structure with an average grain size of 140 nm. With further annealing, the grain size drops to 80 nm (Fig. 5). The structure formed possesses an enhanced strength in comparison with substrate what is confirmed by nanohardness measurements. Homogenization of the surface leads to enhancement of corrosion resistance as well. In general, there are not obstacles to a formation of a surface Ti-Zr alloy of depth up to 10 μm with the above described structure, free of Al and V, by alternation the cycles of film deposition and pulsed melting in a single vacuum chamber. The method described here may be employed as a finishing treatment of medicine implants made of Ti-6Al-4V alloy.

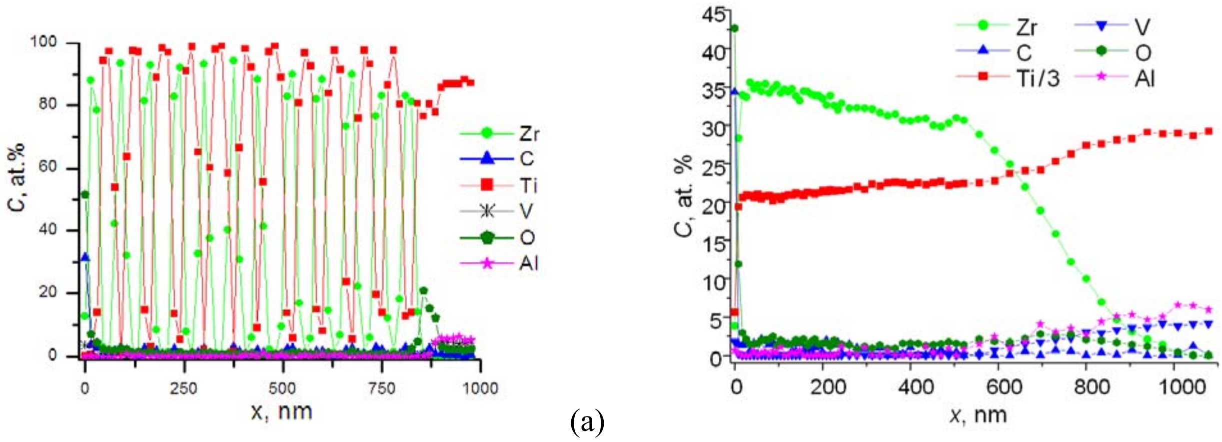
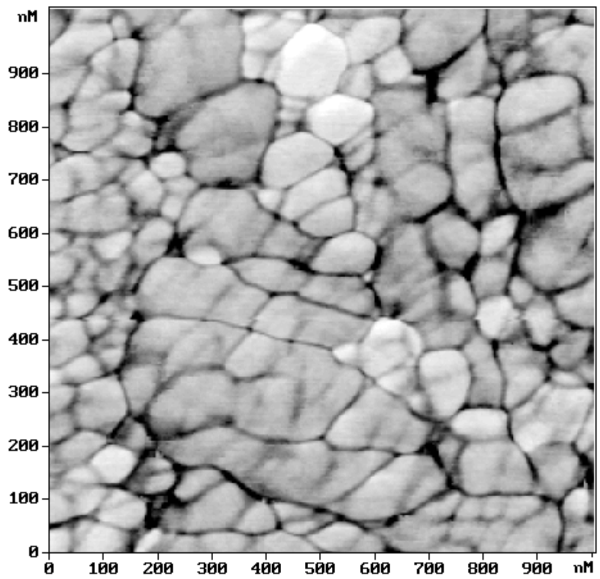
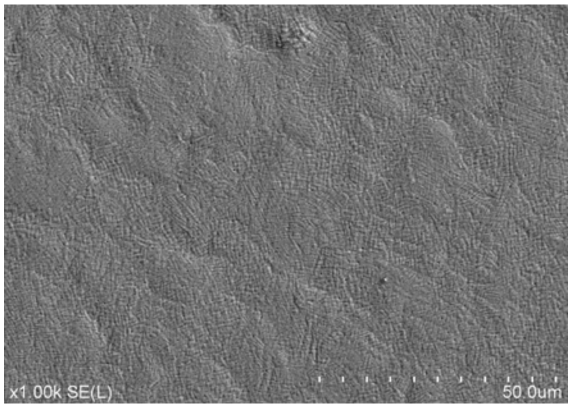


Figure 4. AES profiles of the elements in a Zr(20nm)/Ti(20nm)/…/Zr(20nm)/Ti(20nm)/Ti-6Al-4V system (a) as deposited and (b) after EBEST at 3.5 J/cm^2, N=1.



(a)



(b)

Figure 5. The (a) AFM image and the (b) SEM image of a surface of a zr(20nm)/Ti(20nm)/... …Zr(20nm)/Ti(20nm)/Ti-6Al-4V system irradiated with 3.5 J/cm^2, N=1 followed by vacuum annealing.

The authors suggest the electron-beam facility for polishing and surface engineering designed for specific tasks of customers. The team suggests R&D also to select a bulk–surface system and to create a manufacturing method designed for a specific task. To date, the work study has been done for systems as follows:

- Ta-Fe alloy on an iron (steel) substrate,
- Multilayered Al-Si and Al-C alloys on an aluminum substrate,
- Cu-Steel alloy on a steel (AISI 316) substrate,
- Zr-Ti alloy on a Ti-6Al-4V substrate,
- Cu-Ni alloy on a copper substrate,
- Cu-Al alloy on an aluminum substrate, and
- Ni-Al alloy on an aluminum substrate.

The database on surface alloys on certain substrates is in the stage of continual knowledge acquisition.

References:

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[2] G.E. Ozur, D.I. Proskurovsky, V.P. Rotshtein, and A.B. Markov, "Production and application of low-energy, high-current electron beams", Laser and Particle Beams **21**, 157–174 (2003).

For organizations:

Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences (IHCE SB RAS) was established in 1977. The Institute has its registered office at 2/3, Akademichesky Avenue, Tomsk, 634055, Russia. To date, the Institute employs about 300 persons of the total staff including about 100 persons of the scientific staff. The scientific profile of the Institute includes the activities in directions as follows:

- Pulsed power and production of intense electron and ion beams;
- Production of high-power X-rays, optical radiation, and microwaves;
- Study of high-current vacuum and gas discharge plasmas; and
- Interactions of high-power beams of electrons, ions, and electromagnetic radiation with matter.

The MICROSPLAV Ltd. Company is the branch establishment of the IHCE SB RAS. The Company develops technologies and manufactures the equipment based on intense pulsed electron beams. The electron beams of microsecond duration have proved to be an effective tool for surface modification of metallic materials. They polish the surface and clean it from inclusions. Irradiation by these beams produces homogeneous surface with high corrosion resistance and electrical strength of vacuum insulation. It is possible to form surface alloys using combined equipment including an electron beam and a deposition system of a magnetron type or a vacuum evaporator. The resulting micron-thick surface layers are alloys with a modified chemical composition.

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