ARPN Journal of Engineering and Applied Sciences

SURFACE HARDENING OF ALUMINUM ALLOYS BY INTERMETALLIC PHASES, SYNTHESIZED IN THE PROCESS OF ELECTRON BEAM TREATMENT

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ABSTRACT

The experimental results indicate the possibility of obtaining on the surface of the aluminium alloy layers, modified by alloying with electron-beam technology, significantly increases its wear resistance. Such layers obtained thanks to the initiation of exothermic chemical reactions between substrate and deposited on it a thin film of titanium. In the reaction products was revealed the formation of intermetallic phases.

Keywords: aluminium surface alloying, electron beam, wear resistance.

INTRODUCTION

Specific consumption of materials during production reduced by replacing ferrous metals with light non-ferrous metals particularly with aluminium and alloys thereof steel [1]. The savings in weight when using it is large enough despite the fact that aluminium is more expensive than steel. Besides, it is also relevant to reduce labour intensity in the manufacture of aluminium alloy products, as the treatment thereof is less labour-consuming than the treatment of steel [2].

However, there is a problem associated with improving physical and mechanical, as well as operational characteristics of industrial aluminium alloys, which is still persistent [3]. During operation of pieces made thereof, typically, it is the surface, which is the first to be exposed to the working medium, the first perceiving on itself effects of the working environment [4]. The surface wear typically characterized by mechanical and abrasive wear, associated with mechanical impact or mechanical friction wear, respectively [5]. At present, the problem of increasing the resistance of aluminium alloy parts is solved by developing new, usually high-alloy alloys, by applying special coatings to parts, obtained, for example, using the method of micro arc oxidation, which have wear and corrosion resistance, or anodizing [6-8].

Some researchers suggest improving the wear resistance of aluminium alloys by surface heat treatment and alloying [9-12]. In this case, it is possible to create a near-surface layer having a thickness of several tens of micrometers, which increases wear resistance, by initiating an exothermic chemical reaction between the aluminium base and the metallic film deposited thereon with the formation of intermetallic compounds on the surface. The latter are a class of materials, the use of which in various fields of technology is rapidly expanding due to the unique complex properties [13], including high melting point, increased mechanical strength, heat resistance and heat resistance. Herein we consider the possibility of alloying aluminium with titanium, but it is possible to obtain other compositions. The technology does not rule out the possibility of subsequent application of protective coatings on the object modified by alloying.

EXPERIMENTAL

The treatment based on the task of integration of synthesized intermetallic compounds into the surface layer of the product. The process occurs due to initiation of the chemical reaction between aluminium, present in the substrate, and the titanium film on the surface thereof, applied as a coating, under a schedule of thermal explosion produced by pulse heating the surface with a low-energy high-current electron beam (LEHCEB) [14.15] The treatment conducted in a RITM-SP Unit, which constitutes a combination of a source of low-energy high-current electron beams RITM, and two magnetron spraying systems on a single vacuum chamber. The unit allows depositing films of various materials on the surface of the desired product, and subsequent liquid-phase mixing of the film and the substrate by an intense pulse electron beam [16-18]. The generation of LEHCEB includes the emission of electrons, the formation of a ray in a plasma-filled diode and the transportation thereof in a plasma channel. The adoption of such generation scheme makes it possible to obtain a beam having a microsecond duration (about 5 μs) with a current density of 10^5 A/cm^2 , at an accelerating voltage of 15 to 30 kW, the value of which determines the power density in the beam (Figure. 1). The area of one-time treatment amounts to about 50 cm^2.

The formation in the surface layer of the substrate material of structurally no equilibrium states in the process of its pulsed electron beam alloying is a promising treatment in the creation of wear-resistant complexes before applying the additional protective coating [19,20]. However, the operating of the process of surface alloying makes it difficult enough a large number of control factors, which are determined primarily by the thickness of the surface layer, which should be introduced into the energy sufficient for its heat treatment (melting and partial evaporation). It is the value of the charging voltage, on which the specific beam energy depends; the thickness of the film with alloying components applied using magnetron sputtering, the number of processing cycles and others. Their optimization was carried out, based on the data of metallographic, x-ray and spectral studies for many occasions [21, 22].

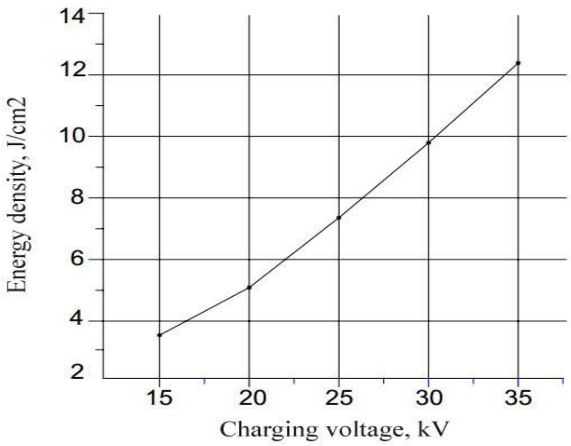

Figure-1. Dependence of the energy density in the electron beam on the charging voltage of the RITM-SP unit generator.

The study was conducted on the specimens of aluminium alloy, containing 1.3% of Cu and 0.26% of Fe as measured by X-ray fluorescence spectrometry. To determine the structural changes on the surface of specimens according to the value of charging voltage of a high-voltage pulse generator, varying between 16 and 20 kW, a series of experiments of irradiating them with LEHCEB conducted. Typically, a series of five or six pulses is enough for the microalloying process to occur all the way through. Before irradiation, specimens coated with approximately 0.2 µm thick titanium film using a magnetron sprayer. To increase the content of titanium on the surface of plates, the treatment made twice. After irradiation, spectrometer indicated the presence of titanium in the near-surface layer, in the amount of up to 1.8%.

The surface layer microhardness was measured using PolyvarMET instrument at a load of 5 g. The wear-resistance tests conducted using CALOWEAR instrument [23], while dry-rubbing the modified aluminium plate with a steel ball diameter 20 mm, at a load of 2N. The crater obtained in the process of rubbing was measured using a MicroCAD lite 3D measuring system [24]. The phase composition of specimens was determined using an X-ray diffraction phase analysis. The diffraction spectra were captured on PANalytical Empyrean Series 2 X-ray diffractometer using CuKα radiation. The phase composition was performed using PANalytical High Score Plus software and ICCDPDF-2 database.

RESULTS AND DISCUSSIONS

The Al-Ti system is a system with a restricted mutual solubility of components. The Ti-Al system alloys possess low mechanical properties and are non-hardenable, but have good processing properties and show excellent corrosion resistance. The only method of improving the strength and plasticity thereof lies in the treatment associated with obtaining titanium aluminides in the structure of alloy, which makes possible to increase the mechanical properties to the required level [25]. The contribution of titanium aluminides associated with low density, high values of strength-to-weight ratio, high-temperature strength, and melting temperature [26, 27].

The analysis of Ti-Al state diagram makes it possible to define four primary structures of titanium aluminides: Ti_3A1, TiAl, AI_2Ti, AI_3Ti. Wherein, the best combination of physical and mechanical properties is demonstrated by Al_3Ti intermetallic compound.

In this case, the mixing of metals of the substrate and the film deposited thereon, which ensures the formation of the surface aluminium-titanium alloy, occurs under the action of an electron beam. This action causes travelling of an elastic wave, which generated during exposure to a pulse electron-beam. At that, there occurs a surge in pressure, density, specific internal energy and other characteristics of the material, spreading through it at supersonic speed (~ 10^3 m/s). Following the shock-wave front, the substance is engaged in motion, gaining a mass velocity, the value of which, though lower than the speed of the shock-wave itself, is still of the same order. The shock compression accompanied by phase, chemical and structural transformations. At that, due to a short duration of the process (~ 10^{-5}s) and to thermal inertia, the heating caused by compression and internal friction, most probably is not the physical factor which determines the behaviour of the material in such conditions [28]. In this case, the main role will be played by mechanical activation of fast-flowing in the matter of physic-chemical processes, which are mainly solid-phase [29].

When the shock wave passes through the dispersing medium, the energy of the shock wave is localized mainly in the surface layer. Thus, the heating of the material to high temperatures is observed in the surface layer. Due to the action of expansion waves and the transferring of heat to inner layers of material, the surface thereof cools rapidly. As a result, in the structure of the near-surface layer, there are observed fine-grain dendrite structures, which are visible after surface alloying with titanium at a 16 and 17 kV charging voltage of high-voltage pulse generator (Figure-2).

Thanks to the good thermal conductivity of aluminium, the temperatures on the surface of the workpiece do not achieve the values required for initiation of chemical reaction to form intermetallic compounds. The X-ray diffraction analysis shows that the specimens have similar diffraction patterns and, subsequently, similar phase composition.

On the substrate diffraction pattern (Figure-3a), apart from the main lines associated with Al, there is additional spikes (denoted by "s") present. The lines at 2θ=34.60, 40.23, 58.17, 69.55 represent the reflection of β-series of Al. The presence of these lines may be explained by high-intensity Al lines, and by the fact that monochromatization of the X-ray radiation when using a mirror for creating a parallel beam, amounts to 95%. The

VOL. 14, NO. 2, JANUARY 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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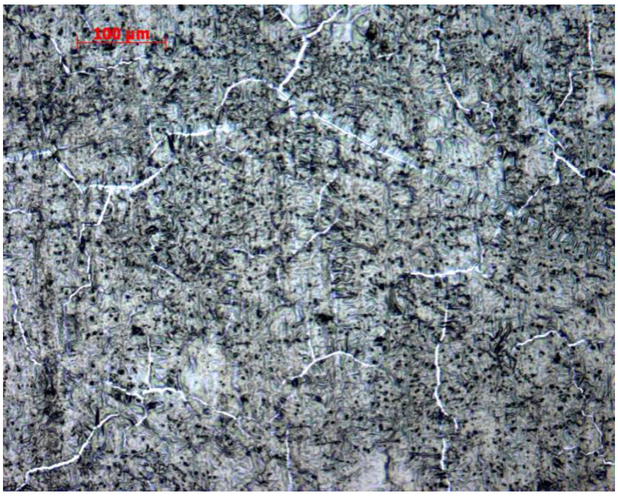
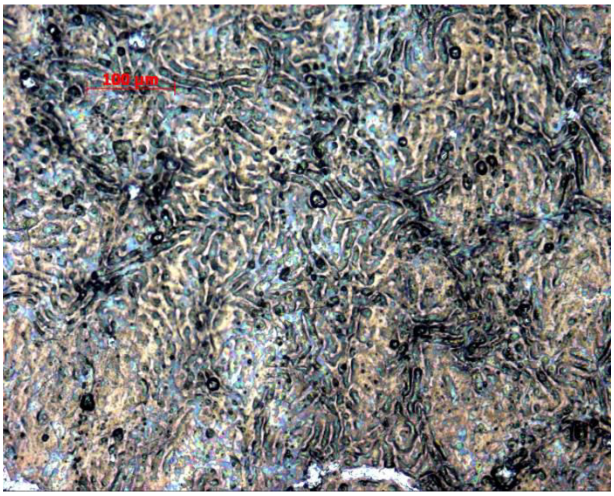
line at 2θ=43.16 probably associated with an additional phase of the substrate with low content. All main and additional reflections of the substrate are also present on the diffraction pattern of modified specimens.



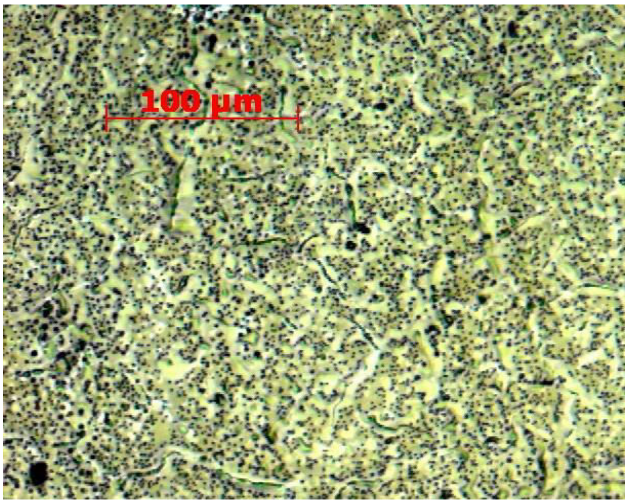
a)



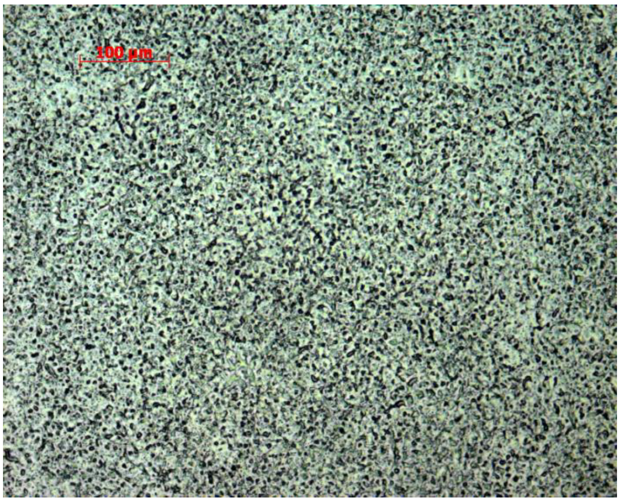
(b)

Figure-2. Structure of the aluminium alloy surface after surface titanium-alloying, a) charging voltage 16 kV, b) 17 kV.

In the surface layers of samples obtained at a charging voltage of 16 kV and 17 kV, the only main phase was found was a high-temperature modification of titanium oxide TiO, which is formed at a temperature above 940 C (Figure-4b, c). In the specimens modified at 17kV, there also can be seen the signs of TiAl phase. Nevertheless, the microhardness on the alloy surface increases to HV_5 = 6.8 MPa (the structure shown in Figure-2b). In should be noted that this increase in microhardness has almost no impact on the wear resistance (Figure-6)



(a)



(b)

Figure-3. Structure of the aluminium alloy surface after surface titanium-alloying, a) charging voltage 16 kV, b) 17 kV.

A small increasing of the charging voltage in the high-voltage pulse generator to 18 kV, which corresponds to an energy density in an electron beam of about 4.2 J/cm^2, helps overcome the potential barrier of intermetallic phase formation. Specimens obtained at a charging voltage of 18 kV and 19 kV, contain TiO and TiAl phases in the surface layer (Figure-4d,e). The main and, probably, the only intermetallic compound contained in the specimens, is the TiAl phase. The Al_3Ti and Al_2Ti phases may be present in small quantities. However, the main lines of these phases overlay the main lines of TiAl phases, and therefore, at low phase content, it is difficult to determine the presence or absence thereof with certainty.

VOL. 14, NO. 2, JANUARY 2019 ISSN 1819-6608
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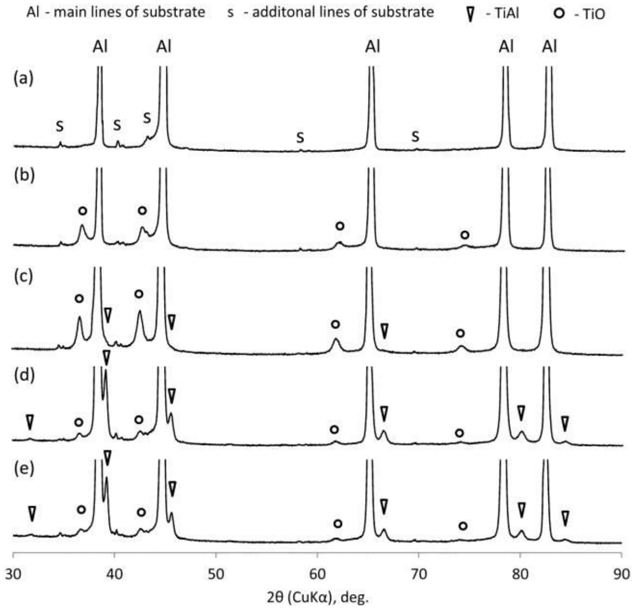

Figure-4. Diffraction patterns of aluminium alloy specimens before and after surface titanium-alloying, a) substrate (aluminium alloy), b) 16 kV, c)17 kV, d) 18 kV, e) 19 kV.

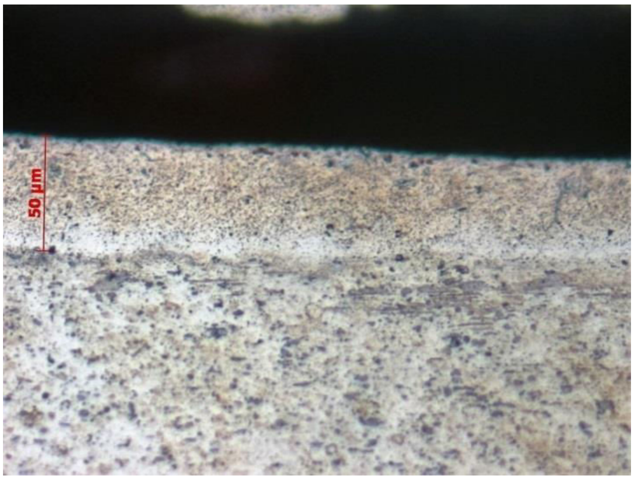

Figure-5. Cross-section of specimen subjected to surface titanium-alloying at a charging voltage of 18 kV.

By increasing the density of energy acting on the object to 4.4 J/cm^2 (19 kV charging voltage), the size of the particles increases to several µm (Figure-3b). Due to this, the microhardness of the surface increases to 8 MPa.

The surface structure changes drastically. Uniformly-distributed particles of the second phase observed (Figure-3a), and the depth of the modified zone may amount to 50 µm (Figure-5). Microhardness of the surface decreased to 5.4 MPa. However, despite this fall, the emergence of the TiAl phase in the near-surface layer significantly slows the wear process. The wear resistance of the specimen has shown a more than twofold increase (Figure-6). The behaviour of the wear-resistance curve of the original object is caused by the steel ball sticking in the crater on the surface of the aluminium alloy.

A further increase in the energy density in the electron beam leads to the evaporation of the near-surface layer together with the titanium film deposited on it. Microhardness HV_5 decreases to 4.5 MPa, it means almost to the microhardness value of the original alloy.

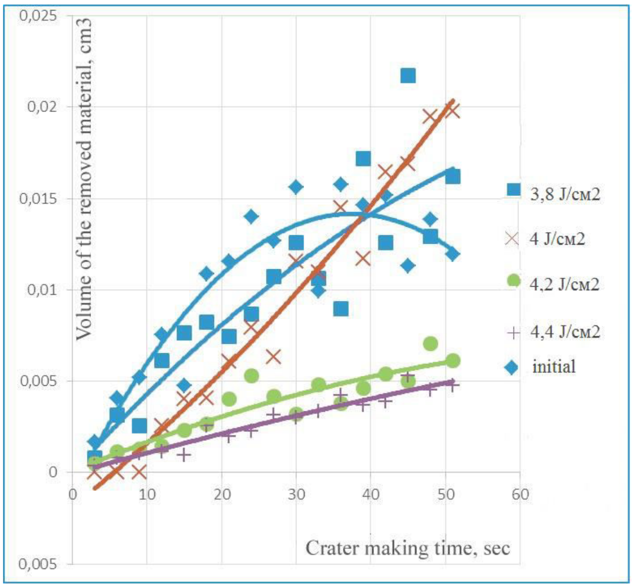

Figure-6. Wear resistance of specimens of aluminum alloy after surface titanium-alloying performed using different treatment schedules.

A "polishing" effect is well visible on aluminium alloys. In case of treatment by positive fusion with the partial evaporation of the surface layer, there occurs refinement of its crystalline structure to submicrometer dimensions, the smoothing of microrelief thereof [30]. The original roughness R_A = 2.5 µm decreases to 0.8 µm. It is possible to recommend performing this operation before the process of surface hardening.

A property of the observed effects lies in their long-term stability and reproducibility.

CONCLUSIONS

The experimental results indicate the possibility of obtaining on the upper layers of the aluminium alloy, modified by surface alloying. Such layers, which made it possible to increase the wear resistance of products (in our case, we obtained an increase in wear resistance in abrasive wear conditions up to three times), were obtained by initiating chemical reactions between the substrate and a thin titanium film deposited thereon. At that, in the reaction products, there was found a formation of a new phase component, particularly a TiAl intermetallic compound.

The formation of a structure in the near-surface layer of material, in this case, is due to a pulsed nature of exposure in a microsecond range. Here, the factors of the microalloying process shall be represented by the energy of the electron beam, dependent on the accelerating voltage, and the thickness of the thin film applied on the surface of the object. Irradiation with insufficient energy in the beam cannot initiate a TiAl formation process, while the excess thereof results in evaporation of most of the film.

The technology described in this article is advisable to use, for example, to reduce the abrasion of the surface of small parts made of aluminium alloys such as gadget corpuses. In addition, the industrial application of surface alloying processes can at least partially replace environmentally dirty anodizing processes, which are usually carried out using chromium, phosphoric or sulphuric acids.

ACKNOWLEDGEMENTS

The financial support provided by the Ministry of Education and Science of the Russian Federation, in the framework of the state task in the field of scientific activity of MSTU “STANKIN” (No 11.1817.2017/4.6). The work is carried out on the equipment of the Centre of collective use of MSTU “STANKIN”.

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