

# Aluminum surface layer strengthening using intense pulsed beam radiation of substrate film system

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**Abstract.** The paper presents formation of the substrate film system (Zr-Ti-Cu/Al) by electric arc spraying of cathode having the appropriate composition. It is shown that the intense beam radiation of the substrate film system is accompanied by formation of the multi-phase state, the microhardness of which exceeds the one of pure A7 aluminum by  $\approx 4.5$  times.

## 1. Introduction

Aluminum and its alloys are widely used in industry due to quite high specific strength, satisfactory corrosion resistance and good mechanical processability. However, aluminum is characterized by low stiffness and durability [1]. To improve the above properties, the surface modification methods are used, among which are hard, extra-hard and wear-resistant coatings, surface treatment by concentrated energy streams, as well as surface saturation with metal and gas atoms [1-3]. All these surface modification methods are applicable for treatment of products made of aluminum and its alloys. It shall be noted that each method has its benefits and drawbacks.

Spraying of coating allows obtaining layers with set stoichiometric composition on the surface, which enables to forecast functional properties. The peculiarity of surfaces obtained with the help of this method is their structure-phase state of the plane interface between the original product surface and coating layers [4]. Presence of such interface raises the issue of the obtained layers adhesion to the substrate.

When obtaining hard layers on the products of aluminum and its alloys the adhesion issue is especially topical because of oxides that are always present on aluminum surface. The second problem caused by the interface plane is a sharp border between the hard layer and the substrate.

Use of concentrated energy streams allows modifying the treated surface by its high-speed melting and further high-speed cooling. Using such approach enables to decrease roughness of material surface and to increase its physico-mathematical, chemical, electrophysical and tribological characteristics by forming multiphase submicro- and nanocrystalline structure [3, 5, 6]. It is worth mentioning that the effect that occurs during treatment with concentrated energy streams is ultimately manifested in complex alloyed materials treatment, especially with regard to modification of mechanical, tribological and fatigue material properties [7, 8]. The above effects are inconsiderably manifested during treatment of aluminum alloys, and even less during treatment of pure aluminum.



The purpose of the paper is to find out and analyze regularities of structure formation and properties of the surface layer of pure aluminum subjected to modification and alloying by melting the film substrate system.

## 2. Materials and experiment method

Pure A7 aluminum was used as material for modification. Combined aluminum treatment was done in the following way. At the first stage, Zr-5 at % Ti-5 at % Cu film 1  $\mu\text{m}$  thick was sprayed on the aluminum surface. The film was obtained with the help of updated "Kvinta" unit for ion and plasma spraying. At the second stage, the formed film (Zr-Ti-Cu alloy) (A7) substrate system was irradiated with intense pulsed electron beam using "SOLO" unit. The structure and element composition of the modified surface were investigated using scanning electron microscopy methods; phase composition was investigated using X-ray diffraction analysis; surface layer properties were defined based on the extent of microhardness.

## 3. Investigation results and discussion

Thermodynamic analysis of possible phase formation that occurs in equilibrium conditions in the Zr-Ti-Cu system (film sprayed on aluminum) and in Zr-Ti-Cu-Al system (film (Zr-Ti-Cu alloy) (A7) substrate irradiated with intense pulsed electron beam) is showed on Figure 1 – Figure 3. The Figures illustrate binary composition phases; possible formation of triple phases is given below.

Al-Cu-Zr System [9]. In triple Al-Cu-Zr system within isothermic triangulated surface 10 intermetallic compounds with narrow homogeneity ranges were found (Figure 1a, phases are marked) and the following triple compounds were singled out:  $\tau_1(14\text{Al}-71\text{Cu}-15\text{Zr})$ ,  $\tau_2(13\text{Al}-14\text{Cu}-73\text{Zr})$ ,  $\tau_3(21\text{Al}-28\text{Cu}-51\text{Zr})$ ,  $\tau_4(\text{ZrCu}_2\text{Al})$ ,  $\text{ZrCu}_2\text{Al}$ ,  $\tau_5(\text{ZrCuXAl}_2\text{-X})$ ,  $\text{Zr}_{25}\text{Cu}_{25}\text{Al}_{50}$ ,  $\text{ZrCuAl}$ ,  $\tau_6(\text{ZrCu}_4\text{Al}_3)$ ,  $\tau_7(\text{Zr}_2\text{CuAl}_5)$ ,  $\tau_8(\text{Zr}_6\text{Cu}_{16}\text{Al}_7)$ .

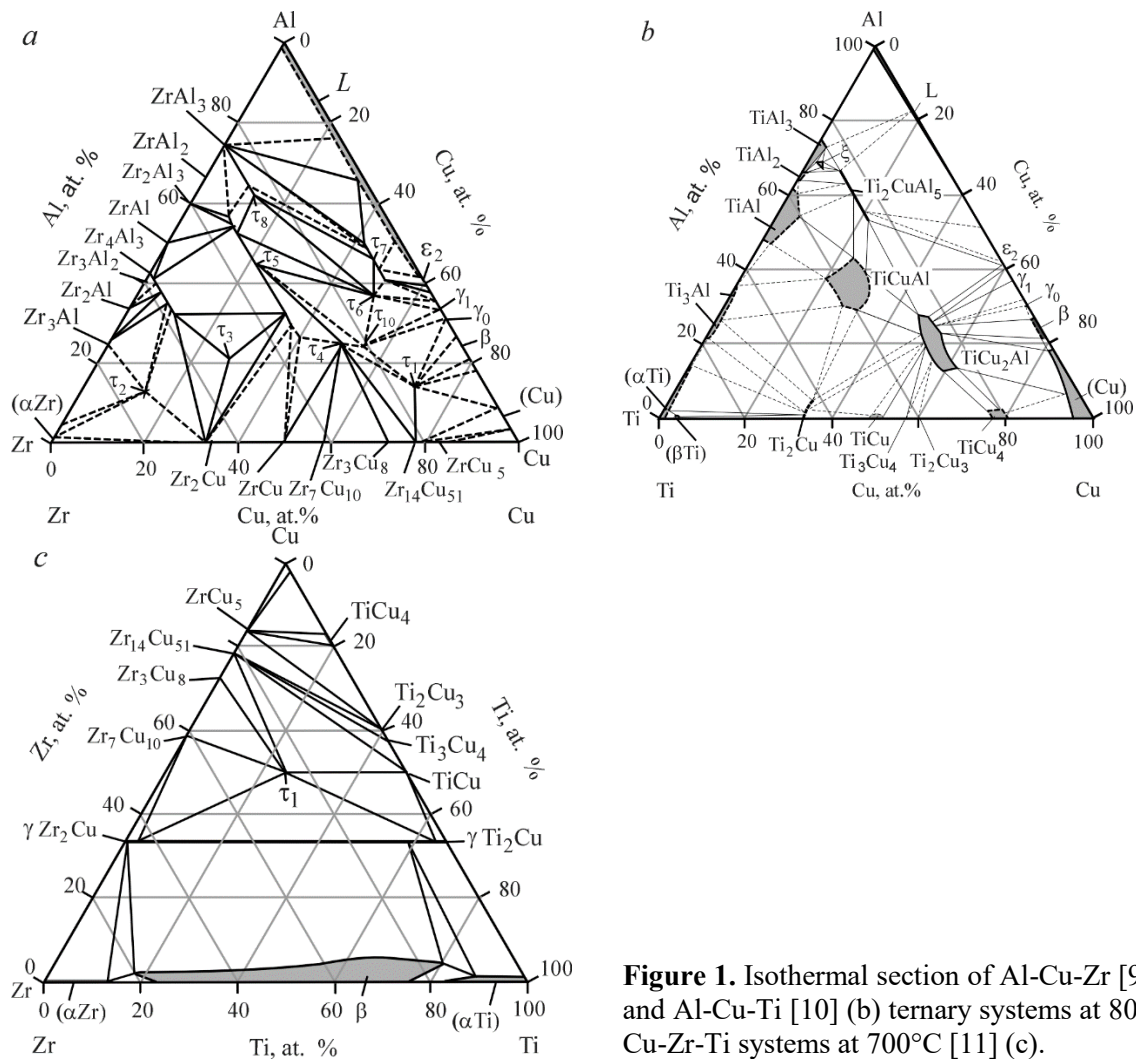
Al-Cu-Ti System [10]. In Al-Cu-Ti triple system intermetallic compounds were found in Al-Ti and Cu-Ti system. Within isothermic triangulated surface the extended homogeneity ranges with the following composition were found (Figure 1b):  $\tau_1(\text{TiCu}_2\text{Al})$ ,  $\tau_2(\text{TiCuAl})$ ,  $\tau_3(\text{Ti}_2\text{CuAl}_5)$ .

Cu-Ti-Zr System [11]. In Cu-Ti-Zr triple system within isothermic triangulated surface only one intermetallic compound  $\tau_1(\text{ZrTiCu}_2)$  was found. It had a certainly defined location with narrow homogeneity range (Figure 1c). At the same time, this system contains an extended range of combination with the C11b structure along the  $\text{Zr}_2\text{Cu-Ti}_2\text{Cu}$  section, in which isomorphous substitution of Ti atoms with Zr atoms occurs.

Thus, in equilibrium conditions quite a big number of double- and multi-element compounds can form in Cu-Zr-Ti ternary system and Zr-Ti-Cu-Al quaternary system.

Investigation of element composition and structure of film (Zr-Ti-Cu) (Al) substrate system formed by electric arc spraying of Zr-Ti-Cu cathode and generated plasma deposition on the pure A7 aluminum samples was done using scanning electron microscopy methods. The analysis results are given on Figure 2.

The analysis of the results given on Figure 2 shows that Zr, Ti, Cu (the sprayed cathode) and Al (substrate) are the key elements of the investigated system. The obtained coating contains a big number of microdroplets (Figure 2 b), which is peculiar to electric arc method of coatings and films application. The microdroplets element composition is similar to the one of the coating itself. Intense pulsed electron beam radiation of the film substrate system in the mode of substrate melting treatment without changing element composition of the coating causes changes in its element concentration. Manifold increase (by  $\approx 3.5$  times) of aluminum concentration was seen in the analyzed surface layer.

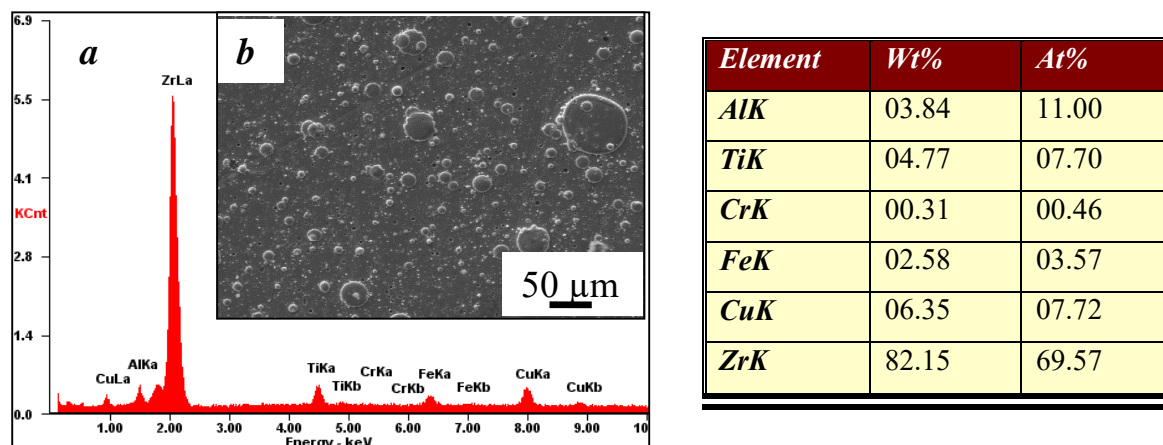


**Figure 1.** Isothermal section of Al-Cu-Zr [9] (a) and Al-Cu-Ti [10] (b) ternary systems at 800°C; Cu-Zr-Ti systems at 700°C [11] (c).

This fact is the evidence of coating melting into the substrate and aluminum seepage through microcraters and microcracks.

The phase composition of the film substrate system was investigated using X-ray diffraction analysis. It was found that coating spraying was accompanied by multi-phase state. The main phases are Al (face-centered cubic lattice,  $a = 0.40722$  nm) (90 mass %), Zr ( $\beta$ -modification, body-centered cubic crystalline lattice,  $a = 0.35967$  nm) (9.6 mass %) and  $Zr_2Al_3$  (0.4 mass %).  $Zr_2Al_3$  formation is the evidence of the substrate alloying with Zr. After intense pulsed electron beam radiation of the film substrate system the phase composition of the surface layer is represented by Al ( $a = 0.40521$  nm; 87.5 mass %), Zr ( $\alpha$ -modification,  $a = 0.32517$  nm,  $c = 0.51814$  nm; 6.8 mass %)  $ZrAl_3$  (5.7 mass %). Manifold increase of  $ZrAl_3$  abundance ratio in the surface layer of the film substrate system confirms the above speculation on the coating and substrate melting in the process of intense pulsed electron beam radiation. Remarkable decrease of aluminum crystalline lattice parameter in the electron beam irradiated material shall be noted. This might be the evidence of the alloying elements' (Zr, Ti, Cu) withdrawal from aluminum crystalline lattice under electron beam thermal action.

The film substrate system was mechanically tested before and after electron beam radiation. The experiment showed that microhardness of the untreated film substrate system doubles compared to the one of pure A7 aluminum sample. And the microhardness of the system after radiation increases by  $\approx 4.5$  times.



**Figure 2.** Energy spectra (a) defined in the process of structure investigation of film (Zr-Ti-Cu) (Al) substrate system (b) using scanning electron microscopy methods. The table presents the results of spectra quantitative analysis (a).

#### 4. Conclusions

As a result of the conducted research the possibility of film (Zr-Ti-Cu) (Al) substrate system formation by electric arc spraying of a certain cathode composition was established. It was found out that intense electron beam radiation of the film substrate system is accompanied by multi-phase state, the microhardness of which is  $\approx 4.5$  times higher compared to the one of pure A7 aluminum.

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