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High-speed thermal plasma deposition of copper coating on aluminum surface with strong substrate adhesion and low transient resistivity

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ABSTRACT

Copper and aluminum are widespread materials and have many applications, especially in the electrical engineering, and their coupling is an important issue. The direct connection of these materials without special preparation leads to increasing the transient resistance and energy loses in the contact place. This paper shows the possibility of copper deposition on aluminum substrates using high-speed thermal plasma jet, generated by a coaxial magnetoplasma accelerator. This method allows forming the uniform coating, having the thickness from 50 to 100 μm, with the strong adhesion to the substrate. It is found that in the considered system the adhesion strength depends on the speed of the material deposition and varies from 1540 MPa to 2520 MPa. Such a strong coupling is achieved due to the presence of the mixing material zone near the interface. The material mixing and the absence of clearly-seen boundary between coating and substrate provides not only the strong adhesion but also allows reducing the transient contact resistance. The value of the transient resistance can be decreased at 2.8 times in comparison with the direct connection of copper and aluminum. The surface roughness of synthesized samples and its influence on the transient contact resistance is also investigated using profilometry analysis. It is shown that increasing the compression force can positively decrease the surface roughness that leads to increasing the contact area and, respectively, to decreasing the transient resistance.

1. Introduction

Copper and aluminum are the most widely used materials in electrical engineering due to their high electrical conductivity, low specific gravity, low costs and ease of production [1–6]. For example, aluminum is often used as cable core material, while copper is common in manufacturing the contact elements for electrical machines, as well as the inlet/outlet buses at the electric power stations. Thus, there is a frequent necessity to connect them to each other. This can be a serious problem, because, while being connected directly, they form a contact pair with the high transient resistance. It leads to increasing the energy loses, continuously heating the contact place, and it results in degrading the contact quality [7]. Everything of mentioned above means that the problem of connecting copper and aluminum with the low value of transient contact resistance is an important issue.

There are several widespread methods to solve the problem of connecting copper and aluminum. It includes the connection with the use of special copper lubricants, the welding processes [8–10], cold upset forging joining [11], and coating deposition by spraying the necessary material. The following deposition ways can be attributed to the last one method: cold-spraying [12–16], plasma spraying [2,17,18], magnetron sputtering [19], and chemical vapour deposition [20]. All of these methods are commonly used when it is necessary both to connect copper and aluminum and to provide the relatively high adhesion strength. This coating property becomes highly important for connecting such type materials, because the coating can peel off the substrate in conditions of changing current loads, that can cause an emergency situation. The higher this parameter, the longer the sample lifetime. For example, the adhesion strength for the magnetron sputtering is equal to 18 MPa [19], for the welding is about 130 MPa [8], for the cold upset forging joining is 163 MPa [11], while the cold spraying shows the best results up to 700 MPa [12].

It is known [13] that the presence of the interface material mixing is the important reason for creating the coating with high adhesion to the substrate due to forming the strong bonds. This bonding mechanism, which is necessary for creating mixing zone, can be implemented by explosive welding [21,22] and cold spraying and strongly depends on the impact velocity. There are some opinions that the adhesion strength can be improved by increasing the material spray velocity [23,24]. Earlier, the possibility was shown to use the high-speed plasma jet, which are generated by a coaxial magnetoplasma accelerator (CMPA), for synthesizing some nanopowders and depositing different coatings [25–28]. This method has several advantages such as the high speed plasma flow (~3 km/s) and the high temperature (~10^4 K) of the plasma flow as well as the ultra-high cooling rate (~10^8 K/s) [25].

This paper presents the result about the possibility of the copper coating deposition on the aluminum substrate using the high-speed

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plasma jet, generated by the CMPA. This method allows not only solving the problem of coupling copper and aluminum but also reducing the transient contact resistivity at 2.8 times in comparison with the their direct contact. The obtained coatings have also the high adhesion (from 1540 to 2514 MPa) to the substrate due to the presence of a interface materials mixing. It is found that in the considered system both the adhesion strength and the transient resistivity, directly depends on the speed of the material deposition.

2. Experimental

The copper coating deposition on the aluminum substrate was carried out in the system, the basic element of which is high-current pulsed coaxial magnetoplasma accelerator (Fig. 1). In the process of its work, this device generates a high-speed plasma jet, which at the exit of the accelerator channel interacts with the substrate, forming a coating.

The CMPA design based principally on the classic Z-pinch type accelerator (1–5, 7), placed into the external inductive system (6). The power supply is provided by the capacitive energy storage (C) with the following maximal working parameters: a charging voltage $U_{ch} =$ 5.0 kV, a charging capacity $C_{ch} = 28.8$ mF. The Z-pinch type accelerator is formed by the central non-magnetic metal electrode (1) with the copper insert in its top (4), the copper barrel-electrode (7), the copper conductive wires, which are used for creating the circuit of the discharge current, the fiberglass insulator (2), and powerful elements (3) to hold the construction. This accelerator is placed in an external inductive field (6), which is necessary for the alignment of the electroerosive wear along the length of the barrel-electrode.

In the moment, when power switches (9) close, the capacitive energy storage is immediately discharged and the current instantly increases in the circuit. After reaching some critical value I_{cr}, the copper conductors electrically explode, forming the arc discharge structure. This arc discharge is accelerated and expanded along the barrel-electrode under the influence of the conductive and inductive electrodynamics forces. It is worth noting that the temperature of the arc discharge in this system can reach 10^4 K [29]. When arc discharge expands, it interacts with the walls of the barrel-electrode. Thus, the necessary working material (copper) is accumulated and converted into the plasma state. An cylindrical solid aluminum substrate is placed at some distance ℓ_{b-s} from the barrel edge. In few microseconds after exiting the barrel, the flow of the copper-containing plasma interacts with the substrate, forming a coating.

In the considered system, a series of experiments was carried out to deposit the copper coatings on the aluminum substrates. The copper electrodes were made of copper tubes Cu-DHP M1 ("Almet" company, Russia) with the copper content not less than 99.9%. The aluminum samples were made of technical aluminum Al99.0 with aluminum content not less than 99.0% ("Almet" company, Russia). They were in the cylindrical form with a diameter of 10 cm and 2 cm thickness. The main working parameters of the synthesis process, such as the current in the circuit and the voltage on the electrodes, were registered using a resistive voltage divider, a Rogowski transformer and an oscilloscope Tektronix TDS1012. The charging voltage and the charging capacity were the same in all experiments and equal to 3.5 kV and 12 mF, respectively. All experiments were carried out under normal conditions in an argon atmosphere.

In order to choose the distances from the barrel-electrode edge to the aluminum target, the plasma shot was made in the free space of the working chamber using the identical power settings. Fig. 2 shows the photogram of the plasma flow and its development in the volume after exiting the barrel-electrode. The recording was carried out using high-speed camera Photron Fastcam SA1.1 through the special protective glass. According to the research results, the law of the plasma velocity attenuation was found and the corresponding curve was built. When the capacitive energy storage has the parameters as mentioned above, at the exit of the accelerator the flow speed is maximum and reaches 4.5 km/s. Based on the collected data, the distances between CMPA edge and substrate were chosen. All the other working parameters are shown in Table 1.

The obtained aluminum samples with copper coatings were investigated by various analytical techniques. In order to determine the coating thickness, the special cross sections of the samples were prepared. For this purpose, the part of the substrate with the deposited coating was cut out and placed in a special hollow-cylindrical holder, the inner space of which was filled with epoxy resin. These samples were placed in air until the moment they became fully hard. After that, they were polished using both a polishing machines Forcipol and diamond paste.

2.1. Scanning electron microscopy

The analysis of the structure and coating thickness was carried out using the cross sections of the coated aluminum samples and an optical microscope Olympus GX – 71. Hitachi TM 3000 scanning electron microscope was additionally used to measure the width of scratches, inflicted on the surface during measuring the adhesive properties.

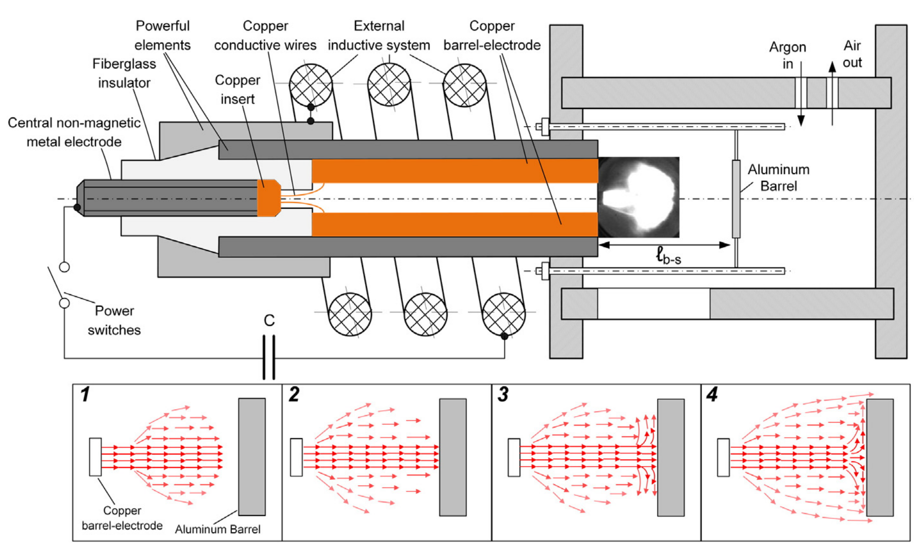

Fig. 1. Sketch map of the CMPA-based system. Small figures *1*→*4* show a simple scheme of plasma flow development and its interaction with substrate.