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# Corrosion protection and electrical conductivity of copper coatings deposited by low-pressure cold spraying

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ABSTRACT

Aluminium/copper contacts occur in power networks made of aluminium alloy busbars. Bolted joints of aluminium and copper cause galvanic corrosion of aluminium in the presence of electrolyte. The paper focuses on the effect of different powder morphology and the addition of ceramics on coating porosity and consequently on corrosion resistance and electrical conductivity behaviour. In this work, corrosion protection of copper coatings deposited by low-pressure cold spraying (LPCS) onto AA 1350 aluminium alloy is examined. The coatings were sprayed using two copper powders of different morphology, namely spherical and dendritic ones. These powders were mixed with alumina before spraying in a 50:50 weight ratio and composite coatings were deposited. The coating microstructures were characterized by the scanning electron microscopy (SEM). The measurements of coating hardness in the middle of the coating thickness were carried out. The coating corrosion protection was analysed by polarization measurements. All coatings showed increased corrosion potential as compared to the substrate. The electrical conductivity of coatings was determined by eddy-current measurements and showed coating conductivity up to 63% IACS. Moreover, coatings heat treatment was conducted to further increase electrical conductivity.



## 1. Introduction

In the cold spray method, compressed and heated working gas creates a stream and accelerates powder particles to a supersonic velocity. Particles impact the substrate in a solid state and thanks to high energy, which makes the coating structure homogeneous, deprived of oxides and porosity. The bonding occurs through local plastic deformation of the material on the particle/substrate boundary. Therefore, the deposited coating gains very good mechanical, physical and chemical properties [1–3].

There are two variants of cold spraying: the low-pressure (LPCS) and high-pressure (HPCS) cold spraying. In the LPCS method, due to lower parameters of spraying, applying a metal-ceramic powders mixture is recommended [1,2]. The addition of ceramics to the powder significantly influences metal particles deformation and decreases coating porosity.

The Cold Spray coatings have good electrical conductivity because of the homogeneity of their microstructure and low porosity. The electrical conductivity of Cu coatings deposited with the LPCS and HPCS methods onto steel substrates is about 46% and 96.9% IACS (the International Annealed Copper Standard), respectively [4,5]. The lower conductivity in comparison to a bulk material is caused mostly by non-bonded interfaces as well as the plastic deformation of copper particles during spraying. The process of recrystallization annealing increases further conductivity of coatings [1,4].

The low oxidation state and high density of microstructure also have a positive effect on the corrosion resistance of coatings deposited with the LPCS method [6–10]. According to the literature [6,7] coatings sprayed with dendritic copper as well as copper-ceramic powder (Cu + 50 vol% of $Al_2O_3$ [7]), show high porosity, which leads to substrate corrosion. Much better protection against corrosion is gained by coatings sprayed with spherical copper powder [7]. Moreover Koivuluoto et al. [4] showed that the admixture of ceramics to metal powder significantly improved the density of the Cold Sprayed coating resulting in a decrease of porosity and hence higher corrosion resistance.

In the electrical industry aluminium and copper are the most prominently applied materials. The Al and Cu busbars used in the open-object installations are exposed to the contact with a humid and polluted environment. Moreover, these materials show significant differences in physical and chemical properties. Hence, essential corrosion problems occur in the Al-Cu electrical contacts [11–16]. An aluminium busbar

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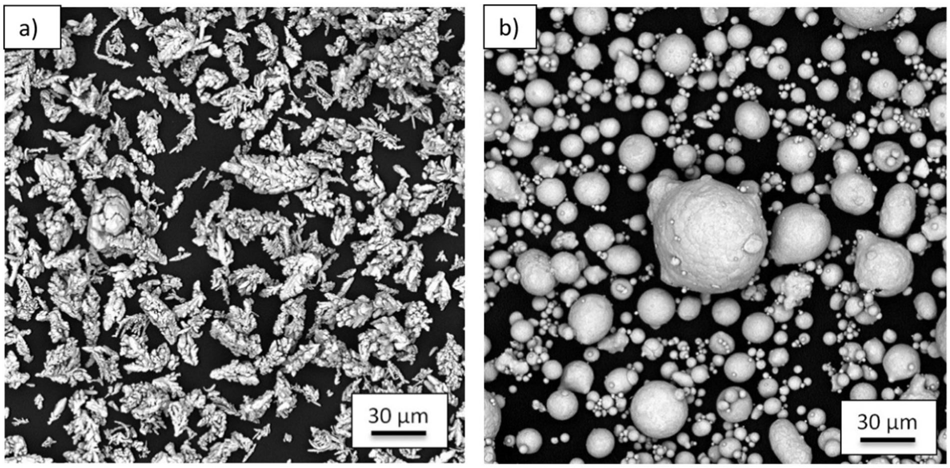


**Fig. 1.** SEM (secondary electrons) micrographs of metal powders used in spraying: E-Cu (a) and S-Cu (b).

bolted with copper in the presence of electrolyte causes galvanic corrosion and thus the oxidation reaction of aluminium surface. This results in the degradation and significant decrease in the electrical conductivity of aluminium busbars. Therefore, the aim of this work is to study corrosion resistance and electrical conductivity of copper coatings deposited onto aluminium surface by the LPCS to protect the Al-Cu contacts.

## 2. Materials and methods

### 2.1. Powders and substrates preparation

Commercially available powders of copper: electrolytic (E-Cu) from Libra (Trzebinia, Poland) and copper spherical (S-Cu) from Sentes Bir (Ankara, Turkey), were used in the spraying process. The granulometry measurements (Analysette 22 MicroTec plus, Fritsch, Markt Einersheim) showed that the size of particles was in the range of $-50 + 10$ µm. The morphology of the metal powders is shown in Fig. 1. Moreover, each powder was mixed with $Al_2O_3$ (mean diameter of 29 µm) in a 50:50 weight ratio before deposition (KOS, Kolo, Poland). The S-Cu powder was produced by gas atomizing and was spherical. The E-Cu powder was produced by the electrolysis method and the particles shape was dendritic. Ceramic powder ($Al_2O_3$) was prepared by crushing and its particles had an irregular shape.

The substrate materials were plates of aluminium alloy AA1350 (99.5 wt% of Al) with dimensions of $7 \times 35 \times 50$ mm and 7 mm thick discs having diameter of 15 mm. The substrates surface was activated by sand blasting under a pressure of 0.6 MPa using alumina sand (mesh 20) and reached surface roughness $R_a = 9.5$ µm (Form Talysurf 120 L profilometer, Taylor-Hobson, Leicester, UK).

### 2.2. Design of spray process experiments

The coatings were sprayed using a DYMET 413 (Obninsk Center for Powder Spraying, Obninsk, Russia) set up which includes a heater and a de Laval nozzle having an outlet diameter of 5 mm. A spraying gun was attached to the manipulator (BZT Maschinenbau GmbH, Leopoldshöhe, Germany) operating in 3 axes: x, y and z. The spraying parameters are summarized in Table 1. Air was used as the process gas and the distance between next spraying beads was 3.7 mm. Prior to polarization and electrical conductivity measurements, the coatings were machined to the thickness of about 200 µm.

### 2.3. Microstructure characterization

The metallographic examinations of powders and coatings were carried out using a SEM Phenom G2 pro microscope with a secondary electrons detector (Eindhoven, The Netherlands). The metallographic cross-section of the coatings had been etched using $(NH_4)_2S_2O_8$. Moreover, semi-quantitative analysis using ImageJ software was prepared to check the amount of $Al_2O_3$ and porosity in the deposited coatings. Deposition efficiency was measured as a ratio of coating mass to the powder mass used to deposit the coating.

### 2.4. Coatings heat treatment

The copper coatings were heat treated to increase the electrical conductivity of the material. Therefore, the coatings were annealed using a Czylok FCF7SM furnace (Jastrzebie-Zdroj, Poland) at a temperature of 400 °C with holding time of 2 h and protective atmosphere ($H_2$).

### 2.5. Hardness measurements

Hardness was measured with the use of a Digital micro Hardness Tester MMT-×7 MATSUZAWA CO., LTD (Akita, Japan). Three different forces (1.961, 4.903, and 9.807 N) were chosen for each type of coating to eliminate errors resulting from the heterogeneous content of ceramic particles or pores. The measurements were conducted in the middle of a coating with the load application time of 15 s.

**Table 1**
Spray parameters and coatings thickness.

| Spraying parameter | | | | | | |
|---|---|---|---|---|---|---|
| Powder | No. of coating runs | Process gas preheating temperature [°C] | Gas pressure [MPa] | Linear speed [mm/s] | Powder feed rate [g/min] | Spray distance [mm] |
| E-Cu | 1 | 600 | 0.9 | 10 | 40 | 10 |
| E-Cu + $Al_2O_3$ | 1 | | | | | |
| S-Cu | 2 | | | | | |
| S-Cu + $Al_2O_3$ | 3 | | | | | |

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