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Miljojkovic, J., Simunovic, G., Vukelic, D., Tadic, B.

# ANALYSIS OF APPLICATION POSSIBILITIES OF SHORT-CIRCUIT EFFECTS IN METAL COATING TECHNOLOGIES

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**Abstract:** *Short-circuit effects are well known and widely used in various technologies, ranging from arc welding to latest research on the application of short-circuit effects in 3D printing technologies. The paper presents the results of the research related to the analysis of application possibilities of short-circuit effects in metal coating technologies. In addition to the literature review, the paper presents theoretical background and results of preliminary experimental research.*

**Key words:** *short-circuit effects, metal coating, energy in contact zone*

**Analiza mogućnosti primene efekata kratkog spoja u tehnologijama nanošenja metalnih prevlaka.** *Efekti kratkog spoja su poznati i široko primenjeni u tehnologijama, počevši od elektrolučnog zavarivanja pa do najnovijih istraživanja vezanih za primenu efekata kratkog spoja u tehnologijama 3D štampe. U radu su prikazani rezultati istraživanja vezani za analizu mogućnosti primene efekata kratkog spoja u tehnologijama nanošenja metalnih prevlaka. Pored pregleda literature u radu su izložene teorijske osnove i rezultati preliminarnih eksperimentalnih istraživanja.*

**Ključne reči:** *efekti kratkog spoja, nanošenje metalnih prevlaka, energija u zoni kontakta*

## 1. INTRODUCTION

Conventional constructional materials are often unable to provide reliability and durability to equipment. The solution to these problems involves change in properties of the surface layers of products by means of depositing functional coatings on machine parts. Varying properties of different coatings have resulted in their wide usage in machine building, transport industry, instrument engineering, electronics and other industries [1]. Coatings and coating deposition techniques are investigated because of the economic drive to reduce wear of materials [2] and the refinement of technology often requires an innovative approach. This paper considers the potentials of short-circuit effects application in metal coating technologies. Short-circuit effects are well known and they are widely used in various technologies, ranging from arc welding to the latest research on the application of short-circuit effects in the 3D printing technologies.

Metal inert gas (MIG) welding has been modified with the low heat input method such as cold metal transfer technology (CMT), thus the process is called CMT-MIG welding, where the filler is deliberately retracted immediately after the natural occurrence of the short circuit. Implementation is related to welding of thin sheets and dissimilar combination of materials [3], [4]. The controlled short-circuit metal inert gas (CSC-MIG) welding system operates using the short-circuit deposition method and uses a control system that allows the user to set the arc length, arc time, current, and several other welding parameters. The CSC-MIG welding system was successfully used for the deposition of tungsten carbide/nickel (WC/Ni) coatings using hardfacing electrode wire [2]. Investigation of microstructure and tribological behavior of the Fe–Cr–B-based coating fabricated by a controlled short-circuit process (CSC-MIG welding) has lead to the following conclusion: at low heat input, there was some porosity in the weld and evidence that the bonding to the substrate was not complete. With higher heat inputs, the alloy was deposited and bonded metallurgically onto the 1020 carbon steel substrate with negligible cracks and porosity [5]. When dealing with welding based on short-circuit metal transfer, some authors focus on the current decrease rate, as the determinant factor in the MAG welding stability [6], as well as the contact force and the duration of the current flow, as factors related to the probability of forming a weld [7]. The controlled short-arc technology was successfully used to clad temperature sensitive materials [8].

The wire and arc additive manufacturing (WAAM) is a direct energy deposition (DED) additive manufacturing process derived from welding that uses a metallic wire as filler metal and an electrical arc as a heat source to produce the wire melting. It has a high deposition rate, with a low cost of raw materials, minimum material losses and it can be used for manufacturing of large parts. For the purpose of implementing cold metal transfer (CMT) process in WAAM, a fixed CMT welding torch is added to the 3D print system [9]. WAAM is gaining popularity in the fabrication of 3D metal components, but it has its limitations: the process is hard to control due to its inherent residual stress and distortion, which are generated by the high thermal input from its heat sources. Aluminum alloy, titanium alloy, stainless steel, nickel alloy, and mild steel are the additive materials that are often used in the WAAM [10]. In order to efficiently transfer the design into the real-world manufacture, in WAAM process the welding paths are often executed by a robotic system. Bearing in mind that conventional robot programming can be time-consuming, especially for complex paths, one way to overcome this problem is to generate robot code directly from CAD models [11]. High degree of automation and geometric freedom of robot-guided wire and arc additive manufacturing are the reasons why construction and architecture sector also sees its potential. While this technique seems promising, there are still technical obstacles which must be overcome. For example, integral material properties depend on the weld process. High heat input leads to low hardness, coarse grains, and lower elongation [12]. As additive manufacturing (AM) builds up a component through the deposition of materials layer-by-layer, it is also considered a promising alternative for fabrication of the components made of expensive materials such as titanium and nickel in the aerospace industry [13]. Bearing in mind that the arc additive manufacturing (WAAM) is considered a promising technology, researchers are now focusing on the investigation of microstructure and residual stress in order to understand their effects on fatigue crack propagation behavior [14]. All these new technologies rely on electrical arc as a heat source.

## 2. THEORETICAL CONSIDERATIONS

A short-circuit between the conductor with varying cross-sectional area (element 1) and an electrically conductive element 2 is analyzed (Fig. 1).

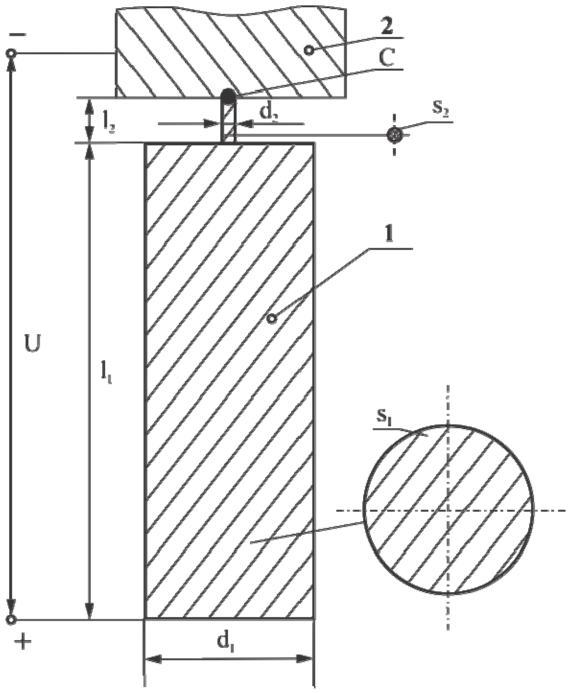


Fig. 1. Short circuit diagram

Element 1 is in fact a resistor connected in a series, whose ohmic resistance is:

$$R = R_1 + R_2 \tag{1}$$

That is:

$$R = \rho \cdot l \; / \; S = \rho \cdot (l_1/S_1 + l_2/S_2) \tag{2}$$

where: $R$ - equivalent electrical resistance, $\rho$ - specific resistance of the material of element 1, $l_1$ - length of conductor, $S_1$ - cross-sectional area of conductor 1, $l_2$ - length of conductor 2, $S_2$ - cross-sectional area of conductor 2.

Based on:

$$S_1 >> S_2 \tag{3}$$

and

$$S_1 \rightarrow \varepsilon \tag{4}$$

as $l_1$ and $l_2$ are real finite values, then:

$$l_1/S_1 \rightarrow \varepsilon \tag{5}$$

where $\varepsilon$ is finite small value. Since $l_1$ has certain finite value, then:

$$l_1/S_1 \rightarrow 0 \tag{6}$$

and it is significantly lower than the value of $\varepsilon$.

Most of the short-circuit energy between elements 1 and 2, in this case, will be accumulated in the contact zone itself, where melting of metallic materials (aluminum, zinc, copper, etc.) can be performed at a voltage of 12 V and power of 100-200 W which, among other things, ensures safe operation. Fig. 2 shows the effect of a short-circuit between aluminum and steel, while Fig. 3 is an image of the rough coating obtained at a voltage of 12 V and at a current of 10 A.

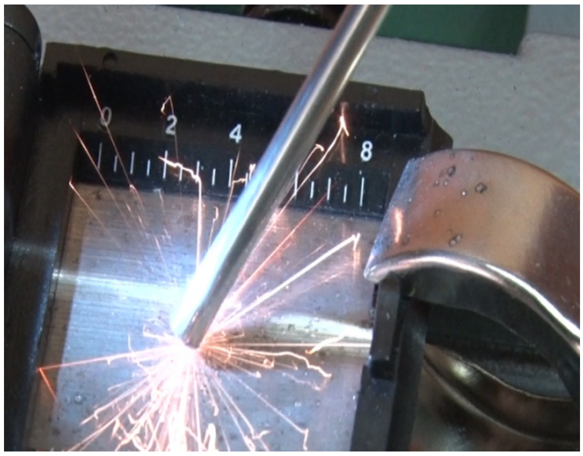

Fig. 2. Effect of a short circuit between aluminum and steel

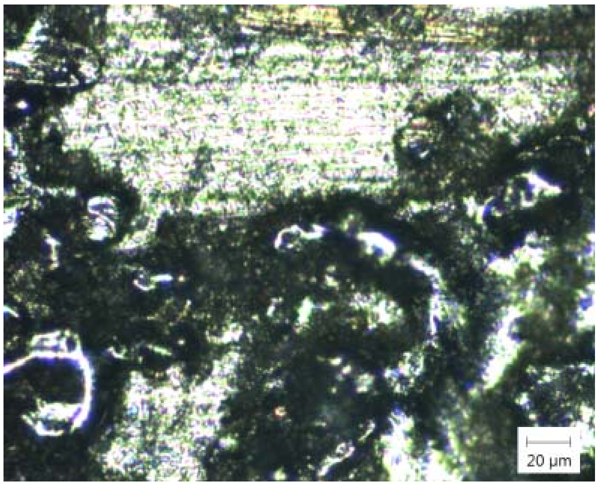


Fig. 3. Rough coating obtained at a voltage of 12 V and a current of 10 A

## 3. RESULTS

By using short-circuit effects, various metal coatings can be applied, provided that the coating material has lower melting point than the base material. Fig. 4 represents the proposed technological solution for deposition of the coating on cylindrical objects.

The element 1 of a cylindrical shape, to which the coating is applied, rotates around the z-axis with an angular velocity $\omega_1$ and moves translationally along the z-axis in both directions at velocity of $V_1$. The object 2, from which the coating is applied (a material with lower melting point), is pressed by a small constant force F along the y-axis. It rotates at a velocity $\omega_2$ around the x-axis and moves translationally along the x-axis in both directions at a velocity $V_2$. It is assumed that a combination of values of angular and translational velocities can produce high quality metal coatings. The size of the contact area made in the vicinity of the theoretical contact (point "C") is very small (detail "C"), ensuring that amount of heat is sufficient, while a quick change of the contact zone shall provide the formation of a high quality metal coating.

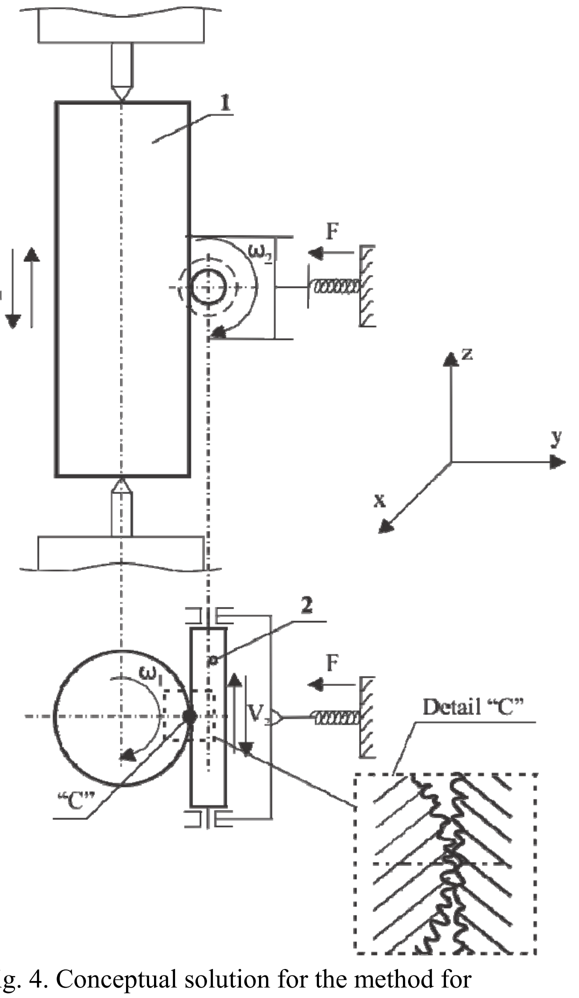


Fig. 4. Conceptual solution for the method for application of coatings to cylindrical objects

Fig. 5 shows the results of preliminary experimental examination, that is, images of the surfaces on which the coatings were applied. Copper coating (Cu) was applied on the carbon steel (1C45). Photographs of the fine coating were taken on a MEIJI TECHNO microscope with 100x magnification. Preliminary results presented in this paper are related to deposition of coating on cylindrical objects, but it should be pointed out that optimal combination of velocities may lead to a successful deposition of coatings to objects of various shapes.

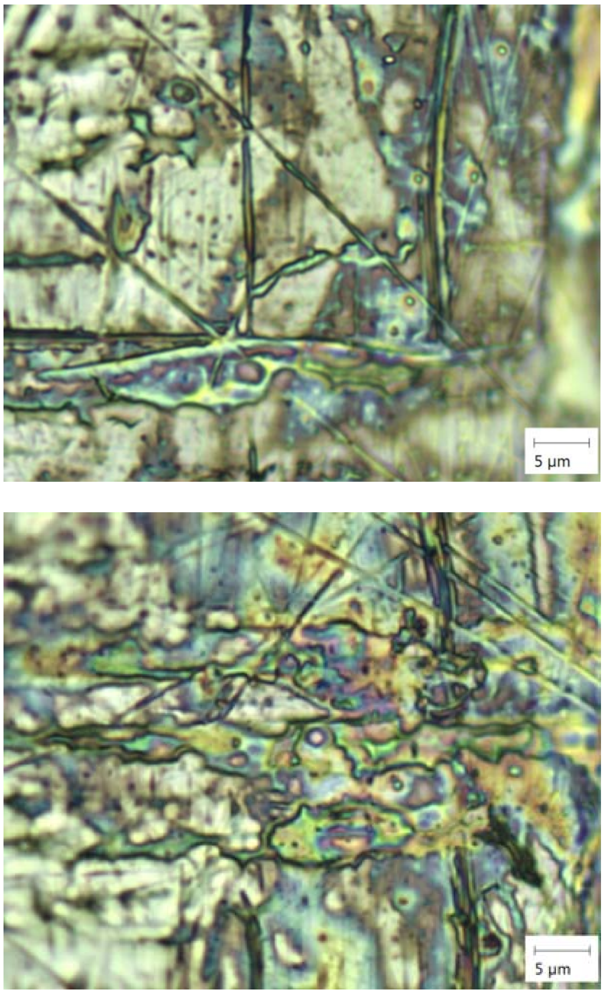


Fig. 5. Images of the fine copper coating with 100x magnification

## 4. CONCLUSION

Literature review shows that short-circuit effects are still in focus of research in the field of contemporary technologies. The theoretical considerations and conceptual solution presented in this paper aims to highlight possible directions of research in the field of application of short-circuit effects in metal coating technologies using small amount of energy concentrated in rapidly changing contact zones. Presented theoretical considerations and preliminary experimental results indicate that the proposed conceptual solution can be implemented as a method for the deposition of metal coatings. By using short-circuit effects, various metal coatings can be applied, provided that the coating material has lower melting point than the base material. In the author's opinion, the proposed method of metal coating application brings new possibilies for research, and new possibilities for the industry, especially regarding the thickness and quality of the coating, which can be achieved by proper combination and optimization of angular and translational velocities with the application minimum constant force at the contact zone.

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***Authors:*** **Jasmina Miljojkovic**, MSc., University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, Kragujevac, Serbia.

**Full Professor Goran Simunovic**, Dr. Sc., Josip Juraj Strossmayer University of Osijek, Mechanical Engineering Faculty, Trg Ivane Brlic Mazuranic 2, Slavonski Brod, Croatia.

**Associate Professor Djordje Vukelic, Dr. Sc.**, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovica 6, Novi Sad, Serbia.

**Full Professor Branko Tadic**, Dr. Sc., University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, Kragujevac, Serbia.

E-mail: jasmina.miljojkovic@fink.rs
goran.simunovic@sfsb.hr
vukelic@uns.ac.rs
btadic@kg.ac.rs