INFLUENCE OF SCANNING CONDITIONS ON COATING PROPERTIES

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1.0 Introduction

Cold spray (CS) is a rapidly developing technology in which the spray particles (in the range of 10 – 150 µm) are fed into a supersonic gas stream accelerated to a high velocity and deposited on a substrate in a solid state [1, 2]. Nowadays this technology is used for different industrial applications such as deposition of corrosion-resistant, electroconductive and thermo-conductive coatings, etc [1, 2].

Thickness uniformity or evenness is very important characteristic of functional coatings [1], which provides uniformity of coating properties. In micro-scale, the thickness evenness is described by roughness parameters, for example by arithmetic mean of the absolute surface departures from the mean line R_a. Typical value of R_a of cold sprayed coating lies in the range from 10 to 15 µm [1]. However for some modern industrial applications such as corrosion protective coatings in automotive and chemical industry, the roughness should be minimized as much as possible [3]. Decreasing of coating roughness could increase its corrosion resistance [1]. Also some paint applications need low roughness to obtain smooth surfaces after painting. There are different ways to decrease roughness but in particular abrasive methods or machining could damage coating. Consequently, there is a need for ways to reduce the roughness of coatings without the degradation of their properties.

Usually cold spray coating is formed by superposition and intersection of large number of spraying tracks. Therefore, spraying strategy strongly influences on coating thickness evenness. It is also should be noted that powder feeders of cold spray systems, for example, feeder of CGT KINETIKS 4000 Cold Spray system, have discontinuous powder feeding defined by distance between apertures on the transport disk of the feeder. Because of the feeding discontinuity, the coating of every single track is formed by several consequent spraying spots having its own thickness profile determined by the geometry of nozzle exit section that complicates the problem of thickness evenness control. Taking into consideration the distribution of particles in spraying spot and overlapping of spraying spots during track spraying, the thickness evenness at fixed powder consumption and final coating mass could be controlled by operating of the scanning velocity, the number of nozzle passes n_l (the number of elementary layers formed by single tracks) and the track overlapping during coating deposition.

Roughness as micro-scale characteristics of coating thickness evenness is defined by particle distribution in spraying spot and by its value of deformation during impact. Particle deformation, particle bonding and coating properties are strongly connected with orientation of particle velocity vector relatively to substrate surface [4]. It is also known that decreasing of spray angle (the angle between jet axis and the tangent to a substrate surface) leads to diminution of deposition efficiency and “riveting” of deposited particles due to intensive “bombardment” of coating surface by non-adhering particles [1]. At the same time high tangential velocity of impinging non-adhering particles could lead to “shaving off” of particles “protruding” from coating surface and therefore could influence on coating roughness.

The purposes of current work were the following:

(i) To investigate dependence of coating evenness on scanning conditions

(ii) To study variation of coating roughness depending on spray angle.

2.0 Materials and Methods

Commercial CGT KINETIKS 4000 Cold Spray system equipped by Type 40 tungsten carbide de Laval nozzle with short pre-chamber was used for coating deposition. Nitrogen was applied as process gas. Commercially available zinc Grillo GZ 3-0 powder was used as the feedstock material. Powder size distribution provided by supplier was –25 µm 75%, –32 µm 98%. Powder feeding rate was $G_p = 0.8 \pm 0.3$ g/min. Powder particles morphology is presented in Figure 1. Coatings were deposited at gas stagnation pressure p_0 fixed at 3.8 MPa and gas stagnation temperature $T_0 = 300$ °C. Rotating sandblasted steel tubes were used as the substrates. The standoff distance was set at 35 mm along nozzle axis.

The general velocity of surface scanning with a nozzle u_{sc} (further in the text mentioned as “scanning velocity”) consisted of two types of velocities: nozzle traverse velocity along the axis of cylindrical substrate and velocity of rotation of cylindrical substrate. These two velocities were recalculated to obtain the value of the resulting scanning velocity. Traverse velocity along tube axis was fixed at 20 mm/s. Therefore variation of u_{sc} was performed only by changing of rotation velocity in the range between 250 to 2000 rpm. Such approach permits to vary in the large range the scanning velocity relatively to substrate surface without high loading on robot with mounted nozzle unit.

The number of layers n_l in this study means the number of turns making by rotating tube (substrate) per time necessary for nozzle to be replaced to the distance equal to diameter of spraying spot (for nozzle Type 40 ~ 9.6 mm). It means that if nozzle traverse velocity is constant, increasing of substrate rotating velocity leads not only to increasing of the scanning velocity but also to increasing of n_l.

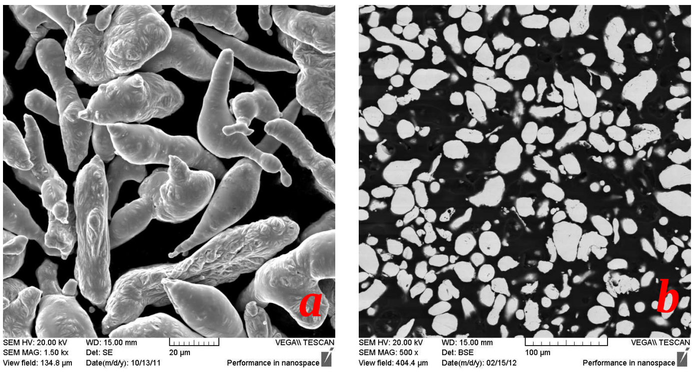

Fig. 1. Micrograph (*a*) and cross section (*b*) of the used Zn powder.

Number of scans means the number of nozzle passes made from the beginning to the end of steel tube along the substrate axe.

In the first series of experiments of the current study u_{sc} was varied in the range 0.5 – 4.0 m/s, number of layers n_l changed in the range between 4 and 33.

Coating thickness h_c was measured with SEM Tescan VEGA3 in 30 points of cross sections made in the direction parallel (15 points) and perpendicular (15 points) to the direction of axe of cylindrical substrate. Therefore influence of track superposition and influence of powder feeding non-evenness on coating roughness were considered. Standard deviation of the coating thickness s_h served as characteristic of coating thickness evenness.

In the second series variation of spray angles was performed. The angle was changed in the ranges $\alpha = 70 – 90$ °, 25 – 70 ° and 0 – 40 ° by changing of nozzle orientation relatively to surface of cylinder. The scanning velocity in these tests was $u_{sc} = 4$ m/s and number of layers was $n_l = 33$. Coating roughness in dependence on spray angle was studied using Mahr Perthometer M1. R_a, R_z (the average peak-to-valley profile roughness parameter) and S (the average spacing between local peaks over the evaluation length) were defined. These values were calculated for each sample as the average values of four measurements of different parts of coating surface. Standard error for each value was calculated.

Deposition efficiency k_d for each sample was measured weighing of tubes before and after spraying.

3.0 Results

3.1. Coating conditions and deposition efficiency in dependence on the scanning velocity and the number of layers. As shown on SEM micrographs of coating surfaces (Figure 2), the coatings deposited at u_{sc} = 0.5 m/s and consisted of 4 layers have some caverns on surface. Analysis of coating microstructure showed that depth of these caverns is equal approximately to half of coating thickness, cavern bottoms are covered by Zn oxide. Increasing of both u_{sc} to 4 m/s and n_l to 33 significantly reduces concentration of the caverns on coating surface.

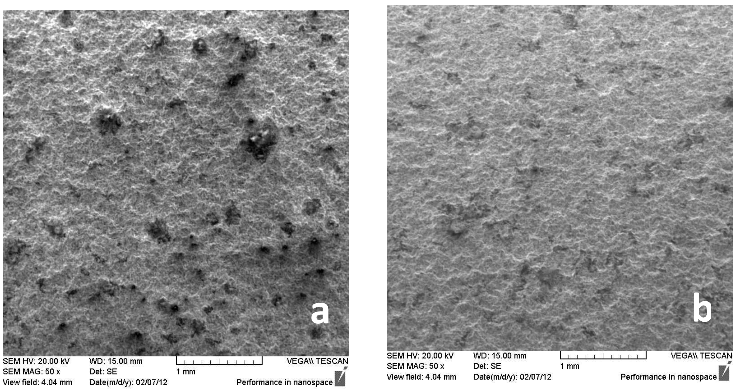

Fig. 2. Morphology of coating surface depending on the scanning velocity and number of layers.
α = 70 – 90 °.
(*a*) u_{sc} = 0.5 m/s, n_l = 4; (*b*) u_{sc} = 4 m/s, n_l = 33.

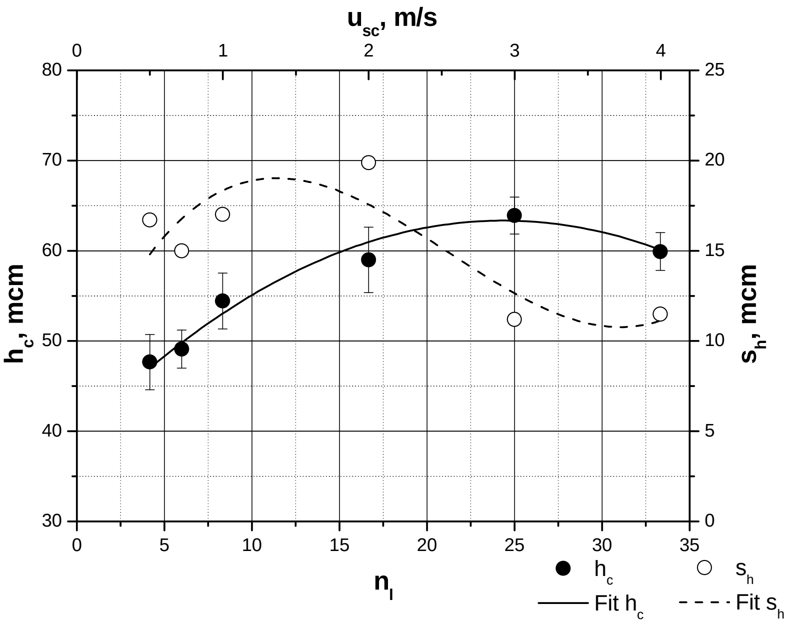

Fig. 3. The coating thickness h_c measured with SEM and the coating thickness sample standard deviation s_h in dependence on the number of layers and the scanning velocity.

Deposition efficiency was approximately equal for all scanning velocities, $k_d \approx 0.58$.

Dependences of h_c, s_h and on the number of layers and the correspondent scanning velocity are shown in Figure 3. Coating thickness slightly increased from 48 ± 3 to 64 ± 2 μm. Standard deviation of coating thickness s_h was ~ 16 µm for u_{sc} = 0.5 – 2 m/s and n_l =4 – 17. Value of s_h decreases in 30% (to 11 µm) if $u_{sc} \geq 3$ m/s and $n_l \geq 25$.

The values of roughness parameter R_a, R_z and S for the different numbers of layers and the correspondent scanning velocities were approximately equal; $R_a \approx 9$ µm, $R_z \approx 58$ µm and $S \approx 125$ µm.

3.2. Influence of spray angle. Typical surface SEM micrographs of coatings sprayed at different angles are presented in Figure 4. The borders of separate particles can be seen on the surface of coatings formed at the angle α = 70 – 90 ^{o}. Reducing of spray angle leads to strong deformation of the particles on the coating surface under the influence of rebounded particles, which can be seen in the micrographs. The boundaries between the particles cease to be distinguishable.

The coating sprayed at α = 25 – 70 ^{o} have no caverns which were observed on the surfaces of the coatings deposited at α = 70 – 90 ^{o}.

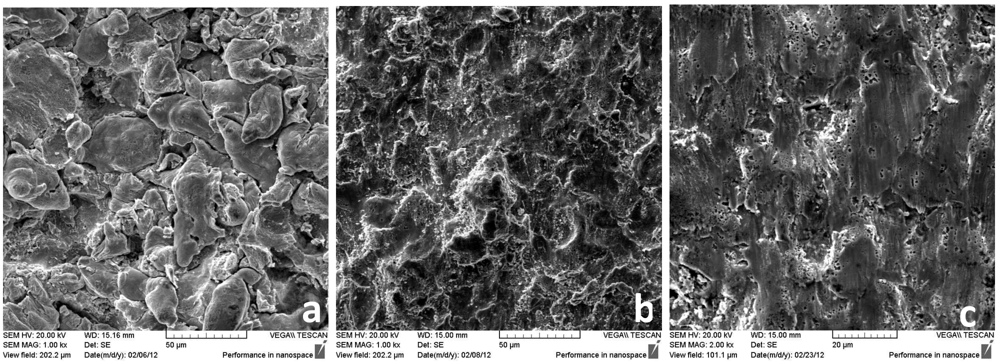

Fig. 4. SEM surfaces micrographs.
Spray angles are α = 70 – 90 ^{o} (*a*), α = 25 – 70 ^{o} (*b*) and α = 0 – 40 ^{o} (*c*).

Surface coating properties and k_d are presented in the table. Increasing of spray angle leads to decreasing of deposition efficiency and coating thickness. At the same time s_h diminished from 11 µm to 0.9 µm (Figure 5), that is an evidence of increasing of coating thickness evenness. Roughness parameters R_a and R_z decreased in more than 2 times if spray angle changed from α = 70 – 90 ^{o} to α = 25 – 70 ^{o} what is the minimal roughness R_a = 3.8±0.1 µm and R_z = 29.9±0.5 µm. After the minimum, roughness parameters show growth up to R_a = 5.2±0.1 µm and R_z = 35.4±0.8 µm at α = 0 – 40 ^{o}.

Spay parameters and properties of coatings deposited with variation of spray angle

α, ^{o}	Track overl. ±0.1, mm	R_a±SE_{Ra} µm	R_z±SE_{Rz}, µm	S±SE_S, µm	h±SE_h, µm	s_h, µm	k_d
70–90	9.2	9.9±0.3	63±2.7	130.5±9.1	60±2	11	60
25–70	12.8	3.8±0.1	29.9±0.5	110.6±2.0	6.7±0.4	2.4	6
0–40	11.6	5.2±0.1	35.4±0.8	134.2±5.6	3.7±0.2	0.9	2

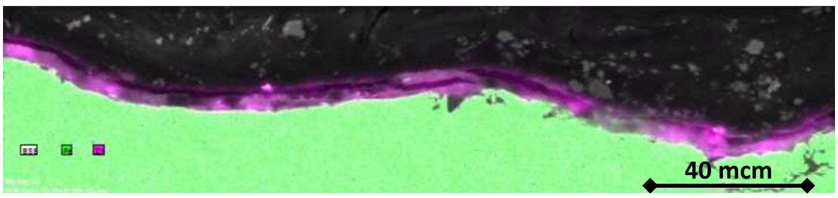

Fig. 5. Profile of coating sprayed at the angle 0 – 40 ^{o} (middle purple line).
Mapping is presented in order to improve contrast between coating and surface.

4.0 Discussion

Experimental results confirmed the assumption that increasing of number of layers with simultaneous decreasing layer thickness (preservation of a given total thickness of the coating) could improve coating evenness. In general it was obtained that spraying on cylinders rotating at high rotation frequency permits to deposit thin even coatings.

The dependence of roughness parameters R_a, R_z and S on the scanning velocity and the number of layers was insignificant.

The proposed approach for decreasing of coating roughness by spraying at a sharp angle was experimentally tested. Experimental results demonstrated that in case of $\alpha = 25 – 70\ ^{o}$ R_a could be decreased to ≈ 3.7 µm. As it is also could be seen from microstructure, dense coating composed from high-deformed particles was formed. At the same time, decreasing of spray angle leads to significant decreasing of deposition efficiency. However, spraying at a sharp angle could be used as "finishing" coating surface treatment in order to decrease resulting roughness of coatings sprayed at a right angle. Spraying at a sharp angle also could be applied for deposition of even coatings with thickness less than 10 microns. The roughness increasing at $\alpha = 0 – 40\ ^{o}$ can be explained by coating discontinuity that was observed in the micrographs. Also the initial irregular profile of sandblasted substrate strongly influences on coating relief because of low coating thickness. Figure 6 demonstrates that the coating "repeats" uneven relief of the substrate. Taking into account the extremely low deposition efficiency ($k_d = 0.02$) in this case it can be considered that spraying in such angle range is unreasonable.

5.0 Conclusion

Dependence of Zn cold spray coatings relief and thickness on spraying strategy was analyzed.

The approach permitting to increase coating thickness evenness by spraying on cylinders rotating at high speed was considered. It was experimentally obtained that increasing of the number of layers with simultaneous decreasing layer thickness (preservation of a given total thickness of the coating) could improve coating evenness. However the dependence of roughness parameters R_a, R_z and S on the scanning velocity and the correspondent number of layers was found negligible.

Influence of spray angle on coating roughness parameters was considered. Experiments demonstrated that spraying at angles less than 70 ^{o} led to decreasing of R_a and R_z of coatings. Spraying at sharp angles could also be used for deposition of thin layers (less than 10 µm) or as finishing coating treatment in order to decrease roughness of coatings deposited at a right angle. It was experimentally demonstrated that such finishing treatment could decrease R_a from ≈ 9 to ≈ 4 µm and R_z from ≈ 58 to ≈ 30 µm. Further reduction of spray angle seems unreasonable because of extremely low deposition efficiency and, consequently, violations of the continuity of the final coating.

It was detected that caverns could be formed on coating surface. It was also obtained that number of such caverns depended on spraying strategy, in particular on the scanning velocity, the number of layers, the track overlapping and spray angle.

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