Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

Taguchi optimization of the thickness of a coating deposited by LPCS

*M. Winnicki**, *A. Małachowska*, *A. Ambroziak*

Wroclaw University of Technology, ul. Lukasiewicza 7/9, 50-371 Wroclaw, Poland

ARTICLE INFO

Article history:
Received 28 April 2013
Accepted 19 April 2014
Available online 13 May 2014

Keywords:
Cold spray
Stereometry
Experiment design

ABSTRACT

The low-pressure cold spray (LPCS) technique is used to produce conducting, anticorrosive, insulating, etc., coatings. In order to increase the efficiency of the process the latter is often automated by attaching the spraying gun to a robot or a manipulator. However, because of the large number of interdependent parameters the thickness of the run obtained in one pass of the spraying gun may range from a few hundred micrometres to as much as a few millimetres. As a result, a coating with varied surface waviness and roughness is obtained. This paper focuses on determining the optimal LPCS process parameters yielding a coating having the desired thickness. For this purpose, the Taguchi method was employed whereby the experiment could be properly designed and the principal parameters having the greatest influence on the process could be determined. The L16′ orthogonal table, four key process parameters and four levels of values for each were used. The input parameters were: powder feeding rate, spraying gun travel velocity, gas pressure and temperature. The output parameter was coating thickness. For verification purposes composite (aluminium + alumina) coatings were deposited.

1. Introduction

The low-pressure cold spray (LPCS) technique has been significantly developed in the recent decade [1–5]. But still no definite findings about the influence of the particular parameters on the thickness, stereometry, waviness and roughness of the coating have been reported. However, it is vital to determine this influence since in some applications the sprayed on coatings do not undergo any further subtractive machining.

The main parameters having an influence on coating thickness are the powder feeding rate, the linear spraying gun velocity, the working gas temperature and pressure, the kind of working gas used (helium, nitrogen, air), the powder particles size and the distance of the nozzle tip from the substrate [6,7]. By appropriately matching the parameters one can obtain a wide range of coating thickness in one gun pass. The research reported in [6] showed that also the substrate material has a significant bearing on coating thickness. Using aluminium, nickel and brass alloys as the substrate material the largest coating thickness was obtained for alloy Al 6061

* *Corresponding author at*: Wroclaw University of Technology, ul. Lukasiewicza 7/9, 50-371 Wroclaw, Poland. Tel.: +48 71 320 27 35; fax: +48 71 320 27 35.
E-mail address: marcin.winnicki@pwr.wroc.pl (M. Winnicki).

http://dx.doi.org/10.1016/j.acme.2014.04.006
1644-9665/

and the smallest for nickel alloy Haynes 556. The authors ascribe this to the low coefficient of compression of the powder particles on such a soft substrate as aluminium. Van Steenkiste and Gorkiewicz [8] studied coating thickness depending on the kind of gas and its temperature and the kind of nozzle. The studies confirmed the key influence of temperature and the kind of gas on the process. However, the results were not subjected to any statistical analysis. The influence of temperature on coating thickness was also confirmed in [9]. In [10] the kind of WC–Co powder was found to have a significant influence on coating thickness. The latter was larger for nanometric powders than for micron powders. Also the number of spraying gun passes was found to play a role: thickness becomes smaller in each next pass [11].

The number of studies focused on determining the optimal coating thickness, particularly the ones based on statistical analysis, is very small. The authors of Ref. [6] studied the thickness of coatings obtained using the low-pressure cold spray technique in order to determine the parameters having the strongest influence on the process. For the particular parameter sets they obtained 0.38–1.89 mm thick coatings and found the maximum thickness of 1.89 to be the optimal one. In other studies the thickness of coatings, which were then subjected to the rupture test, was analyzed. The thickness ranged from 150 μm for Zn [12], through 200–400 μm for Cu and Ni [12,13], to 0.5–3 mm for Al [14–16]. Because of the close dependence between coating adhesion and thickness, prior to rupture tests on coatings obtained using different parameters and materials, one should first determine the optimal thickness. However, no analysis of the influence of the particular process parameters on coating thickness can be found in the literature.

Therefore the aim of this research was to study the influence of the LPCS parameters on the thickness, roughness and waviness of the coatings being deposited. Thanks to experiment optimization the parameter values ensuring the desired coating thickness in one gun pass were determined. Also the roughness and waviness of the surface of the obtained coatings was analyzed. Since in industry some cold sprayed coatings are used without being machined it is essential to distinguish longitudinal and transverse waviness in such coatings. The stereometric parameters closely depend on the process parameters, as shown by the analyses presented below.

2. Experimental methodology

2.1. *LPCS process*

The DYMET 413 low-pressure cold spray device was used in the experiments. In order to obtain comparable results spheroidal Al powder with a particles size of $-50+10$ μm, with an admixture of $-30+10$ μm Al_2O_3 at a ratio of 40/60 wt. %, was used whereby a dense cohesive coating would be produced. The substrate was a 3 mm thick, 50 mm × 100 mm plate made of steel S235JR with a chemical composition: 0.2% C (max), 1.4% Mn (max), 0.045% P, 0.045% S, 0.009% N. Before spraying the substrate surface had been subjected to sand blasting in which alumina had been used as the abrasive. As a result, substrate surface roughness Ra = 5.0 μm had been obtained.

The experiment had been designed using the Taguchi method. In each trial one run was deposited for a distance of 40 mm and thickness h, roughness Ra, longitudinal surface waviness of one run Wa_{1r} and the profile of the coating built in one pass were determined. Then the process was repeated for selected run thicknesses and the process parameters assigned to them to produce coatings. The coating thickness was equal to the sample width and its length comprised five spraying gun passes in axis X and depended on the distance between successive gun passes a. Ultimately, thickness H, roughness Ra, longitudinal surface waviness Wa_1 and transverse surface waviness Wa_2 of the coating were determined.

Exemplary coating topographies are shown in Figs. 1 and 2. If the spraying gun partly covered the previous run a single-step coating would be obtained, as shown in Figs. 1a and 2a. For this coating the inter-run distance amounted to respectively $2a$ and a, at a equal to 1.85 mm. If the runs did not overlap, the gun would return and fill the grooves, whereby a double-step coating would be obtained (Figs. 1b and 2b). In this case, the inter-run distance amounted to respectively $4a$ and $3a$, at a equal to 1.85 mm.

The thickness, waviness and roughness of the coatings deposited by low-pressure cold spraying was measured using the Taylor–Hobson Form Talysurf 120L profilographometer with a gauging point tipped with a diamond cone with the apex angle of 60°, corner radius $r = 2$ μm and an accuracy of 0.01 μm for vertical dimensions and 0.25 μm for horizontal dimensions.

Surface roughness and longitudinal waviness were determined by measuring parameters Ra and Wa_1 along the run for a distance of 30 mm. Run thickness h, coating thickness H and transverse waviness Wa_2 were determined through three measurements taken across the sample, at a distance of 5, 20 and 35 mm from the side edge. Run thickness h was obtained by spraying one bead coating and coating thickness H was obtained by spraying five beads coating. Thickness was measured from the obtained profile, by measuring the distance from the substrate to the run or coating apex.

A round de Laval nozzle, constant distance $l = 20$ mm from the substrate and one gun pass along axis X (Figs. 4 and 5) were used in the experiments.

As shown in [6,13], at a smaller distance of the gun from the substrate the velocity of powder particles is reduced by the generated shockwave. The width of a single run for the nozzle

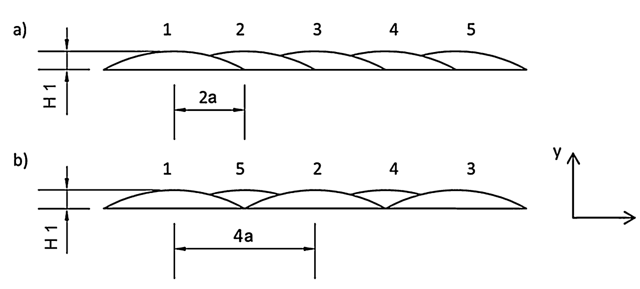

Fig. 1 – A pattern of coating topography with thickness *h* smaller than 1 mm, obtained in single-step (a) and double-step gun pass (b).